U.S. NUCLEAR WASTE TECHNICAL
REVIEW BOARD

REPORT TO
THE U.S. CONGRESS
AND
THE SECRETARY OF ENERGY

1994 FINDINGS AND RECOMMENDATIONS

UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
1100 Wilson Boulevard, Suite 910
Arlington, VA 22209

March 1995

The Honorable Newt Gingrich
Speaker of the House
United States House of Representatives
Washington, D.C. 20515

The Honorable Strom Thurmond
President Pro Tempore
United States Senate
Washington, D.C. 20510

The Honorable Hazel O'Leary
Secretary
U.S. Department of Energy
Washington, D.C. 20585

Dear Speaker Gingrich, Senator Thurmond, and Secretary O'Leary:

The Nuclear Waste Technical Review Board (Board) herewith submits its *Report to the U.S. Congress and the U.S. Secretary of Energy — 1994 Findings and Recommendations* in accordance with the requirements of the Nuclear Waste Policy Amendments Act of 1987, Public Law 100-203.

Congress created the Board to evaluate the technical and scientific validity of the Department of Energy's program to manage the permanent disposal of the nation's civilian spent fuel and high-level radioactive waste. Specifically, the Board is charged with evaluating the DOE's site-characterization activities at Yucca Mountain, Nevada, as well as activities relating to the design of the repository and to the packaging and transport of spent fuel and high-level radioactive waste.

In its 11th report, the Board summarizes the major findings, conclusions, and recommendations that have resulted from Board activities during calendar year 1994. We believe that the information contained in this report will be useful to policy makers and Department of Energy managers and staff as they consider during the coming months the status and future of the civilian radioactive waste management program.

In April 1994, the terms of four Board members ended. These members served on the Nuclear Waste Technical Review Board from its inception in 1989; since then, they have made invaluable contributions to the Board's work. Three of those members provide support in their areas of expertise as consultants pending their reappointment or the appointment of new members with expertise in their areas. We would like to acknowledge the efforts during the

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past five years of Drs. Patrick A. Domenico, D. Warner North, Dennis L. Price, and Ellis D. Verink, Jr., as members of the Board as well as their contributions as consultants to this report.

We thank you for the opportunity to serve the nation and Congress. As our work progresses, we hope to continue to assist you in furthering the goal of safe and cost-effective management of civilian spent nuclear fuel and defense high-level waste.

Sincerely,

John E. Cantlon, Chairman

Clarence R. Allen

Garry D. Brewer

Edward J. Cording

Donald Langmuir

John J. McKetta, Jr.

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Executive Summary

In this 11th report, the Nuclear Waste Technical Review Board (Board) summarizes for the Congress and the Secretary of Energy the major findings, conclusions, and recommendations that have resulted from Board activities during 1994. The Board believes that the information contained in this report, will be useful to policy makers and Department of Energy (DOE) managers and staff as they consider during the coming months the status and future of the civilian radioactive waste management program.

In 1994, the Board and its panels sponsored 11 meetings. In addition to these formal Board and panel meetings, members and staff interacted on numerous occasions with a variety of groups and organizations involved or interested in high-level radioactive waste management issues, including the U.S. Congress; federal, state, and local governmental organizations; Native Americans; grassroots citizen groups; and environmental organizations. Finally, during the past year, various Board members and staff attended a seminar in Sweden and met with experts in the spent fuel and radioactive waste management programs in Finland and Japan. As a result of its efforts during 1994, the Board would like to report the following.

The DOE Has Adopted a New Program Approach

...the new DOE approach incorporates both opportunities and risks...

The DOE's Office of Civilian Radioactive Waste Management (OCRWM) first broached the concept of a new program approach in early 1994. Since then, the Board has heard a number of presentations on the new approach; on May 17, 1994, the Board submitted detailed questions to the OCRWM about the evolving program; and in December 1994, the DOE released its *Civilian Radioactive Waste Management Program Plan*, which documents many of the OCRWM's decisions during the past year, especially those associated with adoption of the revised program approach. The Board's initial impression of the new approach is that it offers the DOE a number of opportunities. The DOE's program approach represents an earnest attempt to refocus DOE resources on the activities required for determining site suitability, and it offers a chance to show program progress.

The Board sees improvement under the new approach in several program areas. The DOE is beginning to achieve better integration of science and engineering with the design and development of the underground exploratory facility. Underground excavation and testing at the site has finally begun, and information from these activities will be critical during site-suitability evaluation. Under the new approach, additional programmatic emphasis is being placed on engineered barriers, extended retrievability, and postemplacement monitoring. Finally, the DOE has recognized that its schedule is very optimistic and will have to be adjusted if more time is required to accomplish the technical evaluation of the site or to complete data gathering and analysis.

At issue is whether sufficient time remains under the current timetable to assemble the required data and perform the appropriate analyses...

In addition to opportunities, however, the new approach has some risks. For example, presently at issue is whether sufficient time remains under the current timetable to assemble the required data and perform the appropriate analyses. The determination of site suitability, now scheduled by the OCRWM for 1998, is the first major milestone in repository development under the new approach. Once the DOE declares the Yucca Mountain site suitable and the Secretary recommends the site to the President for repository development, the DOE's efforts to successfully *demonstrate* that it can construct a safe radioactive waste repository become critical. If the DOE cannot present its case clearly and convincingly to the NRC during the licensing process, the program may be faced with costly and time-consuming delays. The Board believes that to be able to make a *defensible* decision about the site's suitability, the DOE will have to complete a minimal number of basic activities; those activities were outlined in the Board's December 6, 1994, letter to the director of the OCRWM.

Evaluating Site Suitability Requires Some Basics

In its December 6 letter, the Board expressed its views on the basic tasks needed to gain a sufficient understanding of the site and the planned repository. Several important points from the letter follow.

The DOE should continue to develop a waste isolation strategy...

- The DOE should continue to develop a waste isolation strategy to provide an improved technical basis for deciding which site-characterization tests will be completed, deferred, or deleted.
- A clearer definition of "technical" site suitability is needed now to establish a sound basis for future program efforts.

- Perhaps the single most important goal in characterizing the site is predicting (or placing bounds on) the amount and significance of water that could reach the repository, corrode waste packages, and transport radionuclides to the environment.

- Substantially more underground excavation will be needed for a technical site-suitability decision than currently is planned.

- The effects of waste heat on repository performance must be understood well enough to permit confident predictions of (or bounds on) repository performance for alternative thermal loadings.

- A few alternatives for the thermal loading of a Yucca Mountain repository should be carried forward until a better technical basis has been developed for choosing a preferred loading.

The Board remains concerned that program decisions are being driven by overriding worries about meeting the 1998 (site-suitability determination) and 2001 (license application) dates. The existing schedule already may not allow sufficient time to complete the necessary site exploration (e.g., tunnel across the block and explore known and possibly unknown faults at the repository level). Responding to overly demanding schedules increases the risk of programmatic problems arising due to insufficient planning.

Without sufficient data, the DOE will be forced to rely heavily on expert judgment and bounding assumptions...

The schedule raises other concerns as well. For example, some important long-term, and perhaps more expensive, activities (e.g., initiation of in-situ thermal testing and excavation in the Calico Hills formation below the repository) may be delayed or replaced by other less important shorter-duration activities. And, without sufficient data, the DOE will be forced to rely heavily on expert judgment and bounding assumptions. The NRC has yet to formalize how it will assess the use of expert judgment and bounding assumptions in commenting on a DOE recommendation or evaluating the application for construction authorization.

At present, the technical bases for some activities being undertaken by the OCRWM remain unclear; their supporting roles in evaluating site suitability and licensing have not yet been clearly explained. The Board encourages the DOE to continue to develop its emerging waste isolation strategy. Once that strategy has been articulated, it should help identify and quantify the roles of the repository features and barriers that will provide waste isolation; it would justify the data needs, schedules, and funding required to support the technical activities. The waste isolation strategy should be based on the defense-in-depth philosophy that has long been a fundamental aspect of repository planning.

Finally, continuing management problems appear to be impeding effective prioritization of activities and generally may be slowing progress of the excavation of the underground exploratory facility. The Board remains convinced that establishing a geoengineering board, as recommended in

A geoengineering board... could meet regularly with Yucca Mountain project management...to review detailed decisions...when they are first being considered...

the October 1993 Board report on the exploratory studies facility, would greatly help the integration of the scientific and engineering assessment with the underground exploratory facility and thereby aid program progress. Geoengineering boards are common in large underground construction projects, such as subway systems and hydroelectric facilities. Unlike the NWTRB, which has a breadth of expertise and a different mission and reporting mandate, a geoengineering board would be able to focus on the exploration and testing program under way at Yucca Mountain. It could meet regularly with Yucca Mountain project management, staff, and contractors to review detailed decisions early on — *when they are first being considered.* In addition, a geoengineering board would provide the program with technical and scientific continuity.

An Understanding Must Be Gained of the Thermal Effects of a Repository

As part of its new program approach, the DOE has concluded that the best possibility for a successful license application includes a baseline thermal management strategy with a "low" thermal load. The DOE's program approach to thermal management currently is built around three major elements: (1) Flexible designs will be developed for the repository and the waste package. (2) A site-suitability determination, a site recommendation, and a license application to construct will be made in 1998, 2000, and 2001, respectively, assuming that the repository will be operated at a "low" thermal loading. (3) Long-term testing will be carried out to support a possible 2008 application to obtain an operational license to accommodate a higher thermal loading.

At this time, insufficient data and analyses are available to make a scientifically and technically based [thermal loading] choice

Since, a clear definition of "low" thermal loading has not yet been articulated, the strategy is preliminary in concept. Its choice as the program approach to thermal management seems to rest mostly on the belief that, because it might be easier to provide bounding and confirmatory analysis for the strategy, the likelihood of achieving regulatory compliance with this strategy is higher than with other strategies. Until fall 1994, the DOE had limited its evaluation of thermal management options to two, both of which involved thermal loadings at much higher temperatures (waste package temperatures well above boiling for a period of anywhere from 300 to thousands of years). The Board believes that, at this time, insufficient data and analyses are available to make a scientifically and technically based choice of a strategy for the thermal loading of a repository.

More important, however, the DOE should clarify its definition of "low" thermal-loading, and the strategy's implications for the rest of the waste management system (e.g., repository design, waste package design, interim storage needs, etc.) must be evaluated. It is unclear, for example, what the actual areal power density would be under this strategy, how large the repository block would have to be, or how long the fuel would have to be aged before emplacement in a repository. It must be noted that the lower the thermal loading, the more ageing of spent fuel will be needed, or the larger the repository will have to be, or both. The DOE needs to define what data and analyses will be needed to support this concept and how the data will be obtained. Finally, for the program approach to be credible, the DOE must clearly define actions that will be taken if a case *cannot* be made for an amendment to the license prior to 2008 that would allow the repository to operate at a higher thermal loading.

The DOE Should Learn From Others and Avoid Common Pitfalls

The DOE is attempting to refocus and show progress in its civilian high-level radioactive waste management program. As the Board states throughout this report, the new approach provides both opportunities and risks. One real opportunity identified by the Board during the past year is the chance to make good use of the lessons learned by others during site assessments for critical facilities.

Understanding what went wrong or right in other site assessment(s)...could provide helpful insights...directly applicable to the Yucca Mountain project...

During the Board's evaluation of the DOE's program, it became increasingly evident that some commonalities exist during the site assessment process for critical facilities. As a result, the Board decided to learn more about past experiences in site assessment and licensing of critical or highly controversial facilities. At its April 1994 meeting, the Board reviewed the successes and failures of various attempts to site and license critical facilities. Individuals with a wide range of experience in site assessment presented their views on this important issue; experience involved low-level, transuranic, and high-level radioactive waste repositories, hazardous waste facilities, nuclear power plants, dams, and other large engineering projects here and abroad. The Board believes that understanding what went wrong or right in other site assessment cases could provide helpful insights that are directly applicable to the Yucca Mountain project. Lessons learned during the site assessment of other critical facilities that could benefit the DOE are listed briefly below and discussed in detail in Chapter 2.

Site Assessment — It Requires a Strategy

Based on the experience of others, site assessment is a lot more than a collection of data-gathering studies, tests, and analyses; it requires an iterative process that continually looks at the relationships among data-gathering, modeling, and performance assessment. Separating these elements into *sequential* rather than *parallel* efforts increases the possibility of unfocused and costly efforts that also can lead to serious problems at hearings. At Yucca Mountain, assessment efforts have often been sequential rather than parallel.

Determining Site Suitability and Applying for a License Also Require Strategies

Determining site suitability and applying for a license require more than presenting the results of individual scientific and technical studies and analyses; to succeed, the effort requires a strategy. The lesson for Yucca Mountain is that the DOE needs to emphasize the development of a waste isolation strategy that provides a ready and comprehensible explanation of how the proposed repository will protect the public and the environment from the release of harmful radionuclides.

Uncertainties are Unavoidable

Confidence about site and repository issues often seems highest at the beginning of detailed investigations...

Scientific and technical uncertainties are unavoidable in site assessment and the design of critical facilities. The inability to address these uncertainties adequately has been a prime component in the failure to site critical facilities. It is important that the DOE engage the NRC early to get a sense of what the NRC considers to be resolution of an issue for licensing a high-level radioactive waste repository.

Expect Surprises

Surprises exist in any site investigation, particularly those that include underground investigations. Confidence about site and repository issues often seems highest at the beginning of detailed investigations. This is a particularly critical issue with respect to Yucca Mountain because the present schedule assumes that no major surprises will occur. Any long-term strategy and schedule should take the likelihood of their occurrence into account.

Technical and Institutional Overconfidence Does Not Pay

Experience shows that technical and institutional overconfidence — which can lead to arrogance — does not pay; it can result in programmatic and physical failure. It is too early to tell what will happen at Yucca Mountain. A sense of early overconfidence, however, may have already contributed to the DOE's long track record of failing to meet overly optimistic schedules, lack of contingency planning, and unfulfilled promises.

Independent Technical Review is Important

Independent technical review adds both quality and credibility...

Independent technical review adds both quality and credibility. Although the Yucca Mountain project certainly has many outside oversight and review groups, its managers have seemed reluctant to use outside input *during the decision-making process.* An example of this is the rejection of the Board's suggestion (first made in October 1993) to set up a geoengineering board to provide *ongoing* detailed advice to managers and staff at the Yucca Mountain site.

Quality Assurance Counts

Quality assurance is serious business, and this is one area where the DOE appears already to have learned a valuable lesson. During the past several years, the DOE has succeeded in making its quality assurance process more logical and tolerable. However, problems in quality assurance related to the design of the exploratory studies facility indicate that continuing diligence is essential.

Regulations Must Be Clear

Although views differ as to the need for specificity, regulations must be clear; clarity is essential for both applicant and regulator. In the case of Yucca Mountain, this issue is in a state of flux because of the review process initiated by the 1992 Energy Policy Act. As of this writing, no one really knows what the National Academy of Sciences will conclude nor how the EPA and the NRC will react to the NAS recommendations. Clarity and consistency are desired goals for any set of criteria.

Political and Institutional Issues Count, Too

Whether scientists and engineers like it or not, political and institutional considerations are important in waste disposal...

Whether scientists and engineers like it or not, political and institutional considerations are important in waste disposal as well as in many other critical technical issues. Institutional and political considerations have played, and will continue to play, a role at Yucca Mountain. The lesson is that no one should expect site characterization to demonstrate that this site necessarily is the "best" technical choice for the location of a high-level waste repository. Efforts should, instead, concentrate on whether the choice is an acceptable one. As has been pointed out by others, no site will prove perfect.

Process Counts

An NRC attorney underscored one central issue at licensing hearings: the credibility of the written and oral evidence presented. The demeanor of the witness (or *how* the evidence is presented) affects the witness's credibility. Thus far, the DOE generally has been successful in court on procedural issues relating to Yucca Mountain. However, it has not yet been involved in a licensing hearing on technical issues. The format for a licensing hearing has its own special requirements. The DOE will have to prepare itself for the demanding combination of law and science required by this process.

Public Involvement — It's Necessary

Public involvement is another process-oriented issue. There is general agreement that public involvement is necessary. In the case of Yucca Mountain, the Board has stressed the need for more meaningful public involvement before making major decisions. The DOE has held several stakeholder meetings and has proposed involving the public in the site-suitability determination process. If implemented, that proposal would represent progress in this area.

Ultimately, the Board believes that much can be learned from past experience siting critical and other highly controversial facilities that is applicable to the Yucca Mountain program. The DOE *must* look more carefully than it has to date at these experiences and incorporate what has been learned into its strategy and planning. The Board hopes the OCRWM can benefit from the experiences of others and avoid some of their pitfalls while assessing the Yucca Mountain site.

Volcanism — A Difficult Issue Is Moving Toward Resolution

The DOE should capitalize on that progress [in resolving volcanism-related issues at Yucca Mountain]...and maintain momentum in bringing this issue to resolution...

For the second year in a row, the Board has addressed the resolution of difficult technical issues associated with siting a high-level waste repository at the proposed Yucca Mountain site. This time it involves the impact of volcanism on the proposed repository at Yucca Mountain. The Board found that real progress is being made toward its resolution and has identified those elements in the DOE's volcanism program that are facilitating this progress. The DOE should capitalize on that progress; it should proceed with the elicitation of outside expertise and maintain momentum in bringing this issue to resolution. (See Chapter 3.)

Panel Input and Recommendations

As a result of Board and panel activities during this reporting period, the Board makes the following technical recommendations. The Board believes that these recommendations will assist the DOE in achieving its goal of successfully designing and implementing a program to manage the disposal of the nation's civilian spent nuclear fuel and defense high-level waste. (See Chapter 4.)

Structural Geology and Geoengineering

1. The DOE must articulate a clear waste isolation strategy that provides an understandable technical rationale for prioritizing the studies to be completed under the new program approach.

2. The Board recommends that the DOE carry out the minimum suite of underground exploration and associated testing outlined in its December 6, 1994, letter *prior* to the site-suitability decision to ensure that no major surprises will be encountered during the completion of the deferred program.

3. The DOE should develop a more efficient approach to managing the design and construction of the underground exploratory facility; this approach should include the creation of a geoengineering board of expert consultants and greater accountability and incentives for cost-effective and timely performance of the contractors. (This was recommended by the Board in 1993.)

4. The DOE should clarify the "low" thermal management strategy and its relation to the overall waste isolation strategy for the repository. Data needed to support this concept should be defined and the means of obtaining the data determined. For the program approach to be credible, the DOE also must clearly define actions that will be taken if a case *cannot* be made for a high thermal loading during a license amendment prior to 2008.

5. Until contravening evidence becomes available, the DOE should continue to assume that the Ghost Dance fault is "active" and capable of fault displacement within the repository block.

6. The DOE should reevaluate its approach to seismic hazard estimation and place more emphasis on probabilistic hazard estimates and the insights they can provide to guiding the field investigations and resolution of important questions.

Hydrogeology and Geochemistry

1. The DOE working group on ground-water travel time should attempt to establish as early as possible the conceptual model of the unsaturated zone hydrology that it will use in the computation, so that the specific data requirements can be met at the earliest possible moment. In particular, the effort in isotopic data collection and analysis for ground-water age dating should be accelerated and expanded to increase the spatial resolution.

2. Because of the importance of the data that will be gained during underground excavation and because of the significant costs that would be incurred by further delays in construction, the Board recommends that construction of the exploratory facility not be delayed.

The Engineered Barrier System

1. In performing its focused development of a "mined geologic disposal system," the DOE must ensure that *all* assumptions about the repository system are clearly articulated, necessary, achievable, and consistent with current regulations.

2. To support waste package performance predictions, the DOE must develop a formal long-term corrosion research program plan and must support the program at an appropriate and consistent level. Failure to do so risks delaying the repository opening.

3. The Board believes that the DOE should address the issue of general repository requirements for both civilian and defense spent fuel; specific repository requirements applicable to DOE-owned spent fuel should be developed.

4. The Board recommends that the DOE immediately initiate studies to determine what waste forms for Hanford's encapsulated strontium and cesium salts will be acceptable for repository disposal.

5. The Board recommends that DOE's performance assessments address glass waste forms and other defense waste forms at a sufficient level of detail to assist the Office of Environmental Management as it makes decisions about waste forms and waste packages. The Board also recommends that the DOE not delay the completion of its revised total system life cycle cost estimate.

Risk and Performance Analysis

1. The DOE needs to articulate a clear and coherent waste isolation strategy that takes into account the salient characteristics of the Yucca Mountain site, the ability and desirability of engineered barriers to enhance waste isolation, and postulated changes in the basic standard and regulations that will be used to assess the performance of the proposed repository.

2. In light of the successful completion of the 1993 round of total system performance assessments (TSPA), the Board encourages the DOE to continue its program of iterative performance assessment.

3. The DOE needs to make a management and organizational commitment to develop more systematic and effective ways of using total system performance assessment to guide site characterization and to set priorities at Yucca Mountain. The Board suggests that the DOE learn from the manner in which performance assessment was and is being used for the WIPP in New Mexico.

Introduction

In the United States today, civilian nuclear power facilities produce approximately 19 percent of the nation's electric power. One by-product of nuclear energy production, radioactive spent nuclear fuel, is accumulating at the nation's nuclear power plants. Because of its radioactivity, spent fuel will require isolation from the public and the accessible environment for thousands of years.

In 1982, Congress assigned the U.S. Department of Energy (DOE) the responsibility of designing and implementing a system to manage the disposal of this spent fuel; also included for disposal is the country's high-level radioactive waste from defense-related activities. Current plans call for the construction of a deep, geologic repository that would isolate the waste for at least 10,000 years. However, creating a system to manage the disposal of spent fuel and high-level radioactive waste involves more than constructing an underground repository. It involves designing, developing, and implementing a complex system to package, collect, store (for either short or long periods of time), transport, and, finally, dispose of the radioactive waste from public utilities and defense facilities located across the country. All of the components of the system must *work together* safely and efficiently. One major challenge involves demonstrating to the satisfaction of the regulators and the scientific and lay communities that workers in the system — and the public at large — can be protected and that the highly radioactive material will remain safely isolated for the long periods of time that regulating agencies require.

In 1987, Congress chose a site at Yucca Mountain, Nevada, to be evaluated for its suitability as a possible location for a permanent repository. In that same legislation Congress created the Nuclear Waste Technical Review Board as an independent establishment within the executive branch. Congress charged the Board with evaluating the scientific and technical aspects of the DOE's program; the Board submits its findings, conclusions, and recommendations to Congress and the Secretary of Energy. The DOE responds to the Board's recommendations and judgments in writing, and these responses are published in a subsequent Board report without Board comment. The Board's first report was released in March 1990. This is the 11th report in the series. All Board reports are available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 or from the Board's Arlington, Virginia, offices.

Chapter 1
Background

The Nuclear Waste Technical Review Board (Board) addresses issues and makes recommendations in this report that have evolved as a result of activities undertaken by Board members *primarily* between January 1, 1994, and December 31, 1994. In those cases where issues are discussed that were addressed during Board meetings in 1993 or 1995, this is clearly indicated.

Chapter 1 summarizes the Board's activities and reviews several areas that are not discussed in other chapters; for example, Board interactions with the Congress related to the Department of Energy's (DOE) program, meetings with other organizations involved or interested in radioactive waste management issues, and the Board's interactions with experts from programs in other countries. Chapter 2 is devoted to the Board's meeting in April 1994, at which presenters described their experience during site assessment for other critical facilities; some site-assessment efforts succeeded and some failed. The Board was able to identify commonalities among the assessment processes for siting those facilities, and some have direct applicability to the Yucca Mountain site-characterization program. Chapter 3, following a thread established in the previous, tenth report (NWTRB 1994b), looks at another "difficult issue": volcanism. Chapter 4 contains reports from Board panels that have held meetings this reporting period, and chapter 5 presents relevant information gained during a visit to Japan in May 1994.

Summary of Board Activities this Reporting Period

From January 1, 1994, through December 31, 1994, the Board and its panels sponsored 11 meetings. A chronological list of the Board's activities (beginning January 1994 and including those scheduled for the future) can be found in Appendix C. A list of the people who participated in Board- and panel-sponsored meetings has been included in Appendix D. In addition to these meetings, the Board met with experts in the spent fuel and radioactive waste management programs in Japan. Specific insights from recent Board meetings and from the Japanese program are discussed in Chapter 5. Background material on the Japanese program has been included in Appendix I.

Various Board members and staff also attended a seminar in Sweden on environmental impact assessment. The seminar reviewed the process for participating in decision making with a special reference to the siting of a Swedish repository for spent nuclear fuel sponsored by the Swedish National Council for Nuclear Waste (KASAM). The Board co-sponsored a workshop on the engineered barrier system held in Kyoto, Japan, with the Swedish Nuclear Inspectorate (SKI), and KASAM. Finally, during the past year Board members and staff have met with representatives of various organizations here and abroad involved or interested in high-level radioactive waste management issues, including grassroots citizen groups, environmental groups, and Native American groups.

Board Interactions with Congress

On March 14, 1994, Board Chairman John Cantlon, and then member Dr. D. Warner North,[1] testified before the House Subcommittee on Energy and Water Development, Committee on Appropriations. Dr. Cantlon's statement presented the Board's fiscal year 1995 budget request and outlined concerns about the program. Dr. Daniel Dreyfus, director of the Department of Energy's Office of Civilian Radioactive Waste Management (OCRWM), and Nuclear Waste Negotiator Richard Stallings also testified at the subcommittee hearing.

On August 3, 1994, Dr. Cantlon testified before the House Subcommittee on Energy and Power, Committee on Energy and Commerce. Board member Dr. Donald Langmuir also appeared on behalf of the Board to respond to questions from subcommittee members. The hearing was initiated by then chairman of the subcommittee, Representative Philip Sharp, to address concerns about the DOE's civilian high-level waste management program. The full text of the Board's testimony on these two occasions and the Board's answers to written questions received from the Congress after the March 14 testimony are included in Appendix E.

In addition to the Board's regular activities and its presentations before Congress, the Board was asked to make presentations to the Nuclear Regulatory Commission (NRC), the National Association of Regulatory Utility Commissioners (NARUC), and the Nevada Commission on Nuclear Projects. Of the two NRC presentations, one covered the Board's overall views on the DOE's civilian radioactive waste management program; the other concerned the Board's reactions to the DOE's proposed program approach. Presentations before NARUC and the Commission on Nuclear Projects outlined the Board's views on the DOE's new proposed program approach and its perspectives on the DOE's new management reorganization.

Board Views on the DOE's New Program Approach

Chapter 2 of the Board's last report (NWTRB 1994b) stated that, because the DOE's civilian spent fuel program was in flux, no attempt would be made to assess the potential effects of the proposed program modifications. Since that time, the Board has heard a number of presentations and asked questions about the evolving program (e.g., see Appendix F for questions submitted to the DOE on May 17, 1994, about the OCRWM's "Scenario A" and DOE responses to those questions). The following paragraphs present the Board's general assessment of the potential implications for the technical and scientific program of the new program approach.

In general, the Board is encouraged by several aspects of the OCRWM's new program approach because the approach represents an attempt to focus limited resources on what the OCRWM perceives to be those activities required for determining site suitability, for recommending the site to the President, and for applying for a license to begin constructing a repository. The program has adopted a phased process to assess the site and develop the repository design to create its disposal system: (1) In 1998 a decision will be made by the OCRWM about the suitability of the site from a technical and scientific perspective; this is being called "technical" site suitability.[2] (2) If the site is found suitable, in 2000 after evaluating environmental, transportation, and socioeconomic issues through the development of an environmental impact statement (EIS) for the proposed repository, the Secretary of Energy will recommend the site to the President for development as a

1 *Dr. North was one of four Board members whose terms on the Board expired April 19, 1994. Dr. North requested that his name be withdrawn from any consideration for reappointment to the Board as he had decided to put his expertise to work on another DOE program. The other three members, Drs. Domenico, Price, and Verink, have participated as consultants, pending reappointment to the Board or appointment of their successors.*

2 *Unless otherwise indicated, the term "site-suitability decision" as used in this report refers to the DOE's 1998 "technical" site-suitability decision.*

repository. (3) If approved, the DOE would then submit in 2001 an application to the NRC for a license to begin repository construction.

During the past year, the Board has seen an improvement in the OCRWM's integration of science and engineering into the design and development of the underground exploratory facility. Underground excavation and exploration and testing at the site are just beginning, and the information to be gained from these efforts is required for a site-suitability evaluation. Additional programmatic emphasis is being placed on engineered barriers, extended retrievability, and postemplacement monitoring. The OCRWM understands that it is essential to contract for credible expert judgment and outside peer review of the analysis and synthesis of program data. Finally, the OCRWM recognizes that its schedule is very optimistic and may have to be adjusted if it is determined that more time will be required to accomplish the technical evaluation of the site or complete data gathering and analysis.

Currently, debate about the program approach centers primarily on whether the scope of data and analysis that must be assembled to make a site-suitability decision, recommend the site, and apply for a license to construct a geologic repository can be successfully accomplished given expected program funding and the current schedules. The determination of site suitability, now scheduled by the OCRWM for 1998, is the first major milestone in repository development under the new approach. Once the DOE declares the Yucca Mountain site suitable and recommends the site to the President for repository development, its efforts to successfully *demonstrate* that it can site and construct a safe radioactive waste repository are critical. If it does not present its case clearly and convincingly to the Nuclear Regulatory Commission during the licensing process, the DOE may be faced with costly and time-consuming delays.

On October 12, 1994, as part of its efforts to follow the development of the new program approach, the Board held a meeting in Las Vegas devoted to site suitability and the roles of engineered and natural barriers. The meeting was divided into three parts. The first part concentrated on the process by which the OCRWM hopes to assess the suitability of the Yucca Mountain site. Following a DOE presentation, the Board heard comments on the site-suitability process from the NRC, the state of Nevada, and the Nuclear Energy Institute. The second part of the meeting was devoted to a discussion of the status of the OCRWM's waste isolation strategy and scientific priorities during the next few years. The third part of the meeting consisted of a round-table discussion devoted to the importance and roles of engineered and natural barriers in site suitability and repository safety. The round-table discussion was preceded by presentations on approaches to waste isolation and the roles of natural and engineered barriers in the Belgian high-level waste program and in those countries, most notably Sweden, planning to locate high-level waste repositories in a saturated environment in crystalline rock.

The meeting engendered a good deal of interest and discussion. As a result of the information learned at it and from other exchanges on the proposed program approach, the Board decided its best contribution to the program would be encouraging the OCRWM to focus on clarifying the waste isolation strategy (or disposal concept), on site suitability, and on those tests and studies the Board deems necessary for the OCRWM's determination of site suitability at Yucca Mountain.

The Evolving Waste Isolation Strategy

DOE presentations at the Board's October 1994 and January 1995 meetings indicated that a good start has been made toward developing a waste isolation strategy. Once formulated, the strategy should identify and quantify the roles of the repository features and barriers that will provide waste isolation; it should be based on the defense-in-depth philosophy that has long been a fundamental aspect of repository planning. The strategy should provide one of the major bases for planning and prioritizing tests. However, currently, additional information is needed, for example, a decision on the extent to which engineered barrier system features outside the waste packages will be used and a definition and quantification of the features and functions of the geosphere that can serve as essential natural barriers to the release of waste to the accessible environment.

Additional discussion of the need for a clear coherent waste isolation strategy can be found in Chapters 2, 4, and 5.

Other Developments

In December, two months into the fiscal year, the Board received *draft* "Technical Implementation Plans" (TIPs) (DOE 1994a) for most of the activities that the Las Vegas-based Yucca Mountain Site Characterization Office will carry out during fiscal year 1995 directly in support of its site-suitability decision scheduled for 1998. The draft TIPs contain detailed budget and milestone information for many activities, particularly site-investigation activities. The level of description for other activities, notably construction of the North Ramp, is much lower.

In general, the draft TIPs do not show the rationale for undertaking each activity at its particular funding level and milestone schedule. This diminishes their value in assisting the Board to reach a full understanding of what the site-suitability decision is. In many cases, however, particularly for site-investigation activities, the draft TIPs do show the linkage between individual activities and the site-suitability decision. The draft TIPs help the Board understand current activities at Yucca Mountain, but their usefulness is less than complete because they do not address approximately one-third of the current Yucca Mountain work and because they are still in draft form. The Board is looking forward to receiving the full set of final TIPs as they become available.

Also in December, the Board received the OCRWM's *Civilian Radioactive Waste Management Program Plan* (DOE 1994b). The *Program Plan* documents many of the decisions made during the past year, especially those associated with adoption of the revised program approach for managing the DOE's high-level waste program. The *Program Plan* specifies the primary objectives and major milestones to be pursued by the program through the year 2000, provides strategies for achieving those primary objectives, and lays out the specific activities planned as part of each strategy. The *Program Plan* is intended to be a "living document" that the OCRWM will update periodically.

The *Program Plan* is a commendable step toward a more rational and comprehensive planning process for managing the DOE's high-level waste program. Perhaps the most evident shortfall is the plan's lack of a waste isolation strategy to serve as the foundation for the planning effort. The document does include an "isolation demonstration strategy," which contains some elements of the DOE's emerging waste isolation strategy, but there is no apparent linkage of the strategy with the rest of the document. The Board looks forward to future iterations of the *Program Plan* in which the linkage between the different levels of planning can be improved and made more evident.

Board Views on Minimal Exploratory Requirements

On December 6, 1994, a Board letter to the director of the OCRWM explained the Board's views of what will be necessary to gain a sufficient understanding of the site and the planned repository to be able to make a defensible decision about the site's suitability. Major points from the letter are summarized in the box on the next page. The letter can be found in its entirety in Appendix G.

The Board remains concerned that program decisions are being driven by overriding worries about meeting the 1998 and 2001 schedule dates. The existing schedule may not allow sufficient time to complete the necessary site exploration (e.g., tunnel across the block and explore known and possibly unknown faults at the repository level). Responding to overly demanding schedules increases the risk of programmatic problems arising due to insufficient planning. The Board also is concerned that important long-term, and perhaps more expensive, activities (e.g., excavation across the block at the repository level, initiation of in-situ thermal testing, and excavation below the repository in the Calico Hills) may be delayed or replaced by other less important activities. Without sufficient data, the DOE will be forced to rely heavily on expert judgment and bounding assumptions.

The full technical bases for many activities being undertaken by the OCRWM remain unclear to the Board; their supporting roles in evaluating site suit-

Gaining an Understanding of the Yucca Mountain Site

The following is excerpted from the Board's letter on December 6, 1994, to the OCRWM director. The full text of the letter and its enclosed Board comments are included in their entirety in Appendix G.

Ideally, one should be able to discern in the program a direct linkage among a waste isolation strategy, key decisions, technical activities, budgets, and schedules. Although the program has not yet reached this level of integration, the Board is encouraged that the program seems to be moving in this direction.

The Board understands that many details of the program approach have yet to be worked out; however, we have some concerns that we believe should be brought to your immediate attention.

- A clearer definition of "technical" site suitability is needed now to establish a sound basis for future program efforts.
- The DOE should continue to develop a waste isolation strategy to provide an improved technical basis for deciding which site-characterization tests will be completed, deferred, or deleted.
- Perhaps the single most important goal in characterizing the site is predicting (or placing bounds on) the amount and significance of water that could reach the repository, corrode waste packages, and transport radionuclides to the environment.
- The effects of waste heat on repository performance must be understood well enough to permit confident predictions of (or bounds on) repository performance for alternative thermal loadings.
- A few alternatives for the thermal loading of a Yucca Mountain repository should be carried forward until a better technical basis has been developed for choosing a preferred loading.
- The Board believes that substantially more underground excavation than currently is planned will be needed for a "technical" site-suitability decision.

The Board views the new program approach as an excellent opportunity to streamline the scope of site-characterization activities and to improve the technical bases for program decisions. However, completing the necessary site studies and repository design efforts within the current schedule will be a significant technical and managerial challenge.

ability and licensing have not been articulated clearly. An explicit waste isolation strategy that justifies data needs, schedules, and the funding required for technical activities has not been articulated clearly. Furthermore, the OCRWM has not linked a waste isolation strategy to the many components in the TIP.

Finally, continuing management and coordination problems are slowing program progress. For example, until very recently several key management positions were filled by "acting" managers; how responsibilities are divided remains unclear to the Board; and incentives for efficient performance and procurement are remain lacking. Current management problems appear to be impeding effective prioritization of activities and may be generally slowing progress at the site. The Board believes that establishing a geoengineering board, as recommended in the Board's October 1993 report on the exploratory studies facility (NWTRB 1993b), could help to better integrate the scientific and engineering assessment with the underground exploratory facility and thereby help program progress.

The Program Approach and Thermal Management Strategies

On November 17-18, 1994, two of the Board's panels held a joint meeting in Washington, D.C., on thermal management for a mined geologic repository for high-level waste. This meeting resulted from efforts by the management and operating (M&O) contractor begun in May 1994 to develop a better understanding of a "low" thermal management strategy that could be used for the high-level waste program.[3] Up to this time the DOE had limited its evaluation of thermal management options to two: (1) that presented in the 1988 Site Characterization Plan, which considered thermal loadings that in theory would keep waste package temperatures well above boiling for 300 to 1,000 years; and (2) a very high thermal-loading concept that would keep waste package temperatures well above boiling for many thousands of years.[4]

The DOE team working on thermal issues has since concluded that, because of the uncertainties about how the rock will respond to high temperatures, the best possibility for a successful license application lies presently with what the DOE is calling a "low" thermal-loading strategy. This strategy assumes that the areal power density for the repository (the heat that will be released in a repository), which as yet is undefined, would be sufficiently small to have a minimal and predictable disturbance on the rock and the movement of water in the mountain.

The DOE's program approach to thermal management currently is built around three major elements: (1) flexible designs will be developed for the repository and the waste package; (2) a site-suitability determination, a site recommendation, and a license application to construct will be made in 1998, 2000, and 2001, respectively, assuming that the repository will be operated at a "low" thermal loading; and (3) long-term testing will be carried out to support a possible 2008 application for an operational license that would accommodate a higher thermal loading. The "flexible" design for the repository would allow a range of areal power densities and a range of repository sizes.

This strategy is preliminary in concept, and its choice as the program approach to thermal management seems to rest mostly on the belief that, because it might be easier to provide bounding and confirmatory analysis for the strategy, the likelihood of achieving regulatory compliance with this strategy is higher than with the other strategies. The Board believes that any choice of thermal loading at this time would not be based on scientific or technical analyses that show that one given thermal load is better or has inherent advantages over any other. Most important, however, the "low" thermal-loading strategy lacks a clear definition. It remains unclear, for example, what the actual areal power density would be under this strategy, or how large the repository block would have to be.[5]

At the November 1994 meeting, thermal management-related issues were examined from an overall system perspective, considering waste selection at the utilities, ageing, and emplacement and preclosure operations at a repository. Several important issues were identified about which very little knowledge currently exists: (1) Would the large waste packages currently undergoing design be compatible with the "low" thermal management strategy? (2) What ventilation concepts might be useful for removing heat from the repository? (3) What thermal testing would be needed to gain a sound understanding of the "low" temperature thermal management strategy? The Board believes that the DOE should articulate clearly the "low" thermal management strategy with its implications for the overall waste isolation strategy for the repository.

3 *A definition for the "low" thermal-loading strategy has not yet been clearly articulated.*

4 *For an in-depth discussion of thermal issues related to repository development, see the Board's* Fifth Report *(NWTRB 1992a).*

5 *The lower the thermal loading, the more ageing of spent fuel will be needed, or the larger the repository will have to be, or both. If a larger repository is needed, more of the site would have to be characterized at the repository horizon.*

The data that would be needed to support this concept should be defined, and the means of obtaining the data determined. For example, dependence on geologic barriers, such as the Calico Hills formation, may well be crucial in evaluating the viability of the "low" thermal-loading option. Currently, a decision about exploring the Calico Hills formation has not been made, and given the schedule and present operating practices, exploration most likely would not be completed prior to the 1998 date for determining the suitability of the site, perhaps not before the 2000 site recommendation or the 2001 license application dates. A critical issue is what thermal test data will be required to support the license application. At present, no information exists on what data are needed, how they will be used, how they will be obtained by 2001, and how minimal and predictable disturbance will be defined and technically demonstrated. Finally, for the program approach to be credible, the DOE must clearly define actions that will be taken if a case *cannot* be made for a high-temperature repository license amendment prior to 2008.

The DOE's Transportation Program

At its July 1994 meeting in Denver, the Board was briefed on various aspects of the DOE's transportation program. The briefings included an update on the current status of implementing a human factors capability within the transportation program. Since its inception, the Board has urged the DOE to incorporate the principles of human factors and system safety engineering into its program. The DOE has been receptive to the recommendations, but has been slow implementing them. Nonetheless, progress is being made, and some of this was described at the July meeting. Requirements for incorporating human factors and system safety principles have been built into the request for proposals for the multipurpose canister procurement. The Board is encouraged by these developments and looks forward to future progress.

Board Publications

The Board issued two reports during 1994. The *Letter Report to Congress and the Secretary of Energy* (NWTRB 1994a) was released in February 1994; *Report to The U.S. Congress and The Secretary of Energy - January to December 1993* (NWTRB 1994b) was published in May 1994. The *Letter Report* restated a recommendation made in the Board's March 1993 *Special Report* (NWTRB 1993a) that an independent review of the OCRWM's management and organizational structure be initiated as soon as possible. Two recommendations were added: (1) ensure sufficient and reliable funding for site characterization and performance assessment, whether the overall program budget remains level or is increased and (2) build on the Secretary of Energy's new public involvement initiative by expanding current efforts to integrate the views of the various stakeholders *during* the decision-making process — not afterward.

The 1993 summary report reviewed Board activities during 1993, including visits to and presentations on the nuclear waste disposal programs of Belgium, France, and the United Kingdom; the Board's understanding of the radiation protection standards being reviewed by the National Academy of Sciences; and, using "future climates" as an example, the OCRWM's approach to "resolving difficult issues." Recommendations centered on the use of a systems approach in all of OCRWM's programs, prioritization of site-suitability activities, appropriate use of total system performance assessment and expert judgment, and the dynamics of the Yucca Mountain ecosystem. The DOE's responses to these reports have been included in Appendix H of this report. The Board's reports are available from the U.S. Government Printing Office or the Board's Arlington, Virginia, office. (See Appendix J for a brief summary of available Board reports.)

Chapter 2
Lessons Learned in Site Assessment

The DOE's Office of Civilian Radioactive Waste Management (OCRWM) is undertaking a site-assessment program to determine if Yucca Mountain, Nevada, is a suitable location for constructing and operating an underground repository for the permanent disposal of civilian spent nuclear fuel and high-level waste from defense-related reprocessing. If the site is found to be suitable and approved by the President, the DOE will submit an application to the NRC to receive a license to begin construction of the repository. Although the proposed high-level waste repository at Yucca Mountain is in many ways a first-of-a-kind project, it is certainly not the first critical or highly controversial facility ever proposed.

During the course of the Board's evaluation of the DOE's civilian radioactive waste management program, it has become increasingly evident that some commonalities exist during the assessment process for siting critical facilities. As a result, the Nuclear Waste Technical Review Board decided to learn more about past experiences in site assessment and licensing of critical or highly controversial facilities. In April 1994, the Board held a meeting in Reno, Nevada, to review the successes and failures of various attempts to site and license critical facilities. The Board invited individuals with a wide range of experience in site assessment to present their views on this important issue.

Presentations were made based on site-assessment activities involving low-level, transuranic, and high-level radioactive waste repositories, hazardous waste facilities, nuclear power plants, dams, and other large engineering projects here and abroad. Several commonalities emerged, with applicability to the Yucca Mountain project: (1) the importance of having clear strategies for site assessment, site-suitability determinations, and licensing; (2) the significance of uncertainty; (3) the inevitable occurrence of surprises as site investigations proceed; (4) problems caused by technical and institutional overconfidence; and (5) the importance of independent technical review, quality control, and clear regulations. Political and process-oriented issues also were found to be critical — often overriding technical concerns.

The Board believes that understanding what went wrong or right in these cases could provide helpful insights to those wishing to characterize a site and, if the site is found suitable, license a high-level radioactive waste repository at Yucca Mountain.

The following discussion presents the lessons to be learned from the experiences of others in their attempts — successes and failures — to assess and license various sites for the construction of critical facilities. Part 1 provides relevant background material on some individual case histories. Part 2 contains a discussion of common themes among the individual case histories and their particular relevance to the Yucca Mountain program.

Part 1: Site Assessment — Successes and Failures

During the Board's April meeting, individuals described their extensive experience in assessing and/or licensing sites for critical or highly controversial facilities. Some of the cases described were siting failures, others were successes; it is important to note that a "failure" does not necessarily imply that the correct answer might not have been reached from a public policy point of view. Not every side of every issue was presented; the Board's purpose was not to reassess the particular cases involved, but rather to gain insights into the issues that arose, how they were or were not resolved, and their applicability — general or specific — to Yucca Mountain. The following provides background information on the cases as well as what the Board understood to be the views of the individual presenters.

The Martinsville Alternative Site

An example discussed in detail at the meeting was the rejection, after a lengthy (72-day) hearing by the Illinois Low-Level Radioactive Waste Disposal Siting Commission, of the Martinsville Alternative Site as a location for a low-level waste disposal site. Issues relevant to the commission's rejection of the site included the quality of scientific work performed, the level of proof required, and the criteria used. William Hall, one of three commission members who rejected the Martinsville Alternative Site as a disposal location, presented his views of the hearing and site-assessment process. He described the background of the project and the basic logic of the commission's decision. He presented the following major points.

- Politics played an excessive role in selecting the site. He mentioned last-minute maneuvering to get the site under the approving jurisdiction of the city of Martinsville and away from the more disapproving jurisdiction of the county.

- The site was generally inappropriate in that it was upstream from Martinsville in an area of frequent surface ponding, surrounded closely by a river on one side, a stream on the other side, a major road cutting through the site, and the interstate highway, slightly farther away on another side.

- The site is underlain by a glacial till with sand beds that could connect to form an aquifer and which currently feed Martinsville water wells.

- The waste package was based on an assumed, but undemonstrated, lifetime of 500 years.

- There was insufficient knowledge of the source term (i.e., a quantitative description of the amounts of different radionuclides present in the waste).

- There were serious problems with respect to quality assurance of the data and procedures.

- There was little or no independent review of the technical information presented.

- In general, the project was plagued with an unacceptable level of technical uncertainty.

- Public trust, as well as public health and safety, need to be addressed in siting and operating a facility, like the one proposed at Martinsville.

Fred Snider, a subcontractor to a DOE-funded effort supporting the siting of commercial low-level radioactive waste repositories, presented the results of a "lessons learned" and somewhat negative review of the commission hearings. His major points follow.

- The Siting Commission did not appear to accept as adequate existing NRC dose standards, but adopted essentially a *zero release* criterion.

- The commission felt that uncertainty in the source term robbed the analysis of credibility. Better data and a probabilistic approach would have been helpful.

- Failures in quality assurance procedures were discovered in the geochemistry program. This turned out to be an Achilles' heel, undermining the credibility of the entire technical process.

- No one could "prove" that the concrete containers would be leak tight for 500 years, although the proponents never claimed this degree of impermeability. The commission did not have clear standards. These need to be established *before* hearings take place.

- Uncertainties in the ground-water flow models were believed to be a major flaw. The commission equated uncertainties with errors. This issue again indicated that standards and criteria need to be established before assessments take place.

- There was a lack of overall strategy and interdisciplinary coordination in the $60-million site-characterization program. Modeling and performance assessment were carried out independently of field data collection. There should have been iterative feedback to guide the investigations and reduce uncertainties.

- The commission often discounted the credibility of technical witnesses based on their demeanor.

The Waste Isolation Pilot Plant

The federal government plans to dispose of defense transuranic waste in a large mined facility in deep salt beds near Carlsbad, New Mexico. This site, the Waste Isolation Pilot Plant (WIPP), was chosen in 1975 as a successor to a project abandoned at Lyons, Kansas. Since the WIPP is only for transuranic defense waste, the facility is not subject to licensing by the NRC, but is subject to the National Environmental Policy Act, Resource Conservation and Recovery Act of 1976, and the Environmental Protection Agency's high-level and transuranic waste standards. The DOE issued an environmental impact statement for the WIPP in October 1980 and a supplemental statement on the testing phase in January 1990. Although the site has been partially excavated and is ready to begin operations, the demonstration of regulatory compliance is in a preliminary stage. As a result, a decision about whether or not to begin operation is not expected before the year 2000.

Wendell Weart, chief scientist for the Sandia National Laboratories at the WIPP, summarized the lessons that have been learned during the past 20 years of site characterization. His major points are listed below.

- When the site was selected, a lot of attention was paid to avoiding previously drilled boreholes, because a major problem at the unsuccessful Lyons, Kansas, salt site was undiscovered boreholes. The big issues at the WIPP turned out, instead, to be future human intrusion and the presence of brine and salt dissolution features.

- Performance assessment was a powerful tool in helping evaluate and prioritize the research program. Some processes that were not envisioned originally were included later.

- During court battles, the WIPP never lost on technical challenges; it almost always lost on procedural challenges.

- Technical surprises included: the presence of clay seams (undetected in drill cores), which were important in selecting the facility horizon; the existence of brine reservoirs beneath the repository layer; a much faster creep rate in salt than lab tests had forecast; brine seepage in underground excavations in the absence of any thermal gradient; and a much more complex hydrology of the overlying aquifer than originally anticipated. Many of the surprises were only found after going underground, and some led to design changes in the proposed repository.

- Surprises during site characterization will always be used by critics to pursue their case.

- Typically one is most confident of site and repository issues *before* beginning detailed investigation.

- Both the site and the design must be "robust" enough to compensate for uncertainties and natural variations discovered during characterization.

- Site attributes should not be oversold or over simplified until they are confirmed. At the WIPP, overemphasis on the advantages of salt as a dry environment resulted in some loss of confidence when brine was discovered underground.

- Stakeholders must be involved early and meaningfully in issue resolution. The WIPP has generally had a positive experience with the Environmental Evaluation Group, a New Mexico review group.
- Technical and programmatic continuity are important for projects that take a long time to complete.
- Although scientists, regulators, and managers view phased demonstration of compliance positively as “getting on with the job,” many in the public view it as another effort to open the facility earlier.

Gorleben, Lower Saxony, Federal Republic of Germany

In 1977, the state of Lower Saxony designated the Gorleben salt dome as the candidate site for the German high-level waste repository. The disposal concept involves waste emplacement in a salt dome at a depth of about 800 meters. Detailed below-ground exploration was begun in 1986 with the sinking of shaft No. 1; for a variety of reasons, however, delays at the Gorleben site have continued.

Klaus Kühn, director of the institute conducting research for Gorleben, described insights developed during characterization of that site. He gave a short description of the German nuclear program and a history of work done at Gorleben. His major points are listed below.

- The Lower Saxony state government rejected a proposed reprocessing plant at Gorleben because, although it “can be realized from a safety point of view, [it] cannot be carried through politically.”
- Detailed site exploration at Gorleben will be carried out using two deep shafts. Brine was not expected to be a problem.
- Unexpected technical and nontechnical problems have been encountered during shaft sinking. These include one bad weld in a supporting steel ring, the detection of some brine in adjacent drill holes, and the accidental death of a miner. At the time of the meeting (April 1994), shaft sinking had stopped because there was no license for continuation.
- An unexpected tongue of loose sediments was discovered, which lessens the ability of the overburden to act as a natural barrier. Critics claim that the site should be abandoned, but studies indicate that the safety goal (maximum dose to an individual of less than 0.3 milli-Sieverts per year for 10,000 years) can be met.
- Aside from an individual dose limit safety goal, the German criteria are not very specific and allow for margins of discretion when applied to a specific site. In Germany, it is not necessary to find the best site for a repository, only one that will meet the safety goal and is within the margins of discretion.
- A consensus on nuclear energy is desirable. The understanding that a repository is needed must be established in spite of not-in-my-backyard attitudes.
- Licensing and other legal requirements should be clear.
- Licensing criteria should be flexible and not too specific, allowing for the use of a systems approach.
- Unexpected geologic results and technical problems will occur.
- Knowledge of the proposed radioactive inventory in a repository is important for planning. For those countries with changing conditions, estimates of this inventory should be kept current.
- Cost should not be neglected.
- Positive interaction with the public is important but public hearings and discussions seemed to be more driven by fighting “a religious or ideological war against nuclear power” than by solving the problem of siting and constructing a repository.

- An international commission of nuclear waste disposal should be established. Discussion of international repositories should no longer be taboo.

Swan Hills Hazardous Waste Treatment Facility

Professor Walter Harris, a chemistry professor from the University of Alberta, described the *successful* siting and construction of a hazardous waste treatment facility in the province of Alberta, Canada. According to Professor Harris, much of the success was due to the involvement of the public at the local level. His major points follow.

- It would have been a blunder to target the site prematurely. Information was provided and it was then left to the community to invite further discussions and investigations.

- Another site (Ryley) was interested in hosting the waste treatment facility. Although Ryley had certain advantages because of its proximity to the waste producers, the provincial government eventually chose Swan Hills. The committee on which Professor Harris served was told (by the government) that the choice of Swan Hills was political and should not be questioned.

- The suggestion by one committee that the facility be sited at the center of a nine-square-mile block was intended to make the facility appear safe. The suggestion achieved the opposite result in that the need for such a large land area implied an extreme danger.[1]

- It was necessary for all, including the public, to realize that zero release is not a realistic goal.

- The town of Swan Hills received no prior financial inducement, nor does it benefit from direct taxes from the waste facility.

- It is a mistake to pass regulations before the means exist to carry them out. A government only loses credibility when, for example, it prohibits illegal dumping but cannot enforce the ban because no facility exists to legally accept waste.

- Siting waste facilities is mainly a social-psychological-political problem and cannot be solved by primarily technical means. A skilled sociologist was very helpful in achieving success in this case.

- It is very important to set up a base of accurately informed and committed local leadership. In this case, a two-day seminar with local representatives from throughout Alberta was particularly effective.

- Respect for the public, honesty, and openness are required. *We have a problem to solve jointly* is the approach that needs to be developed among all involved.

Four Critical Facilities in California

Lloyd Cluff, geosciences manager at Pacific Gas and Electric Company, described his experience with several critical facilities in California; his focus centered on managing critical safety projects. The projects he described included: (1) the proposed, but never built, Auburn Dam; (2) the successfully constructed New Melones Dam; (3) the proposed, but never built, Point Conception Liquid Natural Gas (LNG) facility; and (4) the highly controversial, yet operating, Diablo Canyon Nuclear Power Plant. He concentrated on issues related to earthquake safety. His main points are presented below.

- The failure to build the *Auburn Dam* is largely due to the builder (the Bureau of Reclamation) designing a doubly-curved, thin-arch dam that probably could not have accommodated two or more inches of earthquake fault displacement at a site where such displacements were viewed as possible, albeit of very low probability. This resulted in a sustained conflict with state authorities. Even a number of the bureau's own consultants viewed possible fault displacement through the dam's

1 *At a recent international meeting in Prague, a French speaker made a similar argument with respect to the geologic disposal of high-level radioactive waste. He maintained that the implied need to bury this waste at great depths made people more apprehensive.*

foundation as credible. The Bureau of Reclamation was so entrenched in its decision to build a thin arch dam that it brought in bulldozers to excavate and find evidence that the faults were not active. In doing so, it destroyed other useful evidence that could have been used in the evaluation. In any case, the key evidence on fault displacement hazard was obtained from regional, rather than local, site geologic studies.

- The *New Melones Dam* is located near the same fault zone that crosses the proposed Auburn Dam site. In this case, the use of an earth and rock fill dam design, which can accommodate some fault movement, and agreement with the state authorities allowed the U.S. Army Corps of Engineers to construct the dam.

- The *Point Conception LNG facility*, which was never built for economic reasons, used a novel approach to resolve long-simmering, highly controversial technical problems regarding seismic safety. The California Public Utilities Commission convened a panel of impartial technical experts that evaluated the seismic safety of the proposed facility. In contrast to legal hearings, lawyers were assigned a secondary role, and the California Public Utilities Commission and the Federal Energy Regulatory Commission approved the panel's work, acknowledging that an efficient legal precedent had been set that provided a high level of confidence on a technically difficult issue.

- In 1984 after a long history of controversy, the *Diablo Canyon Nuclear Power Plant* received its operating license from the NRC. To confirm earthquake safety in light of new (and some old) concerns, a multimillion-dollar, long-term seismic safety program was undertaken. New management in the seismic area, technical workshops, and independent studies by the NRC all were instrumental in the successful completion of this program. The initial wish list of studies planned for this seismic program was trimmed down through a logic tree-based probabilistic scoping study[2] that assessed the relative importance of the individual studies to the overall program.

According to Cluff, ineptness on the part of the applicants, the regulators, and their consultants plagued all the above projects at one time or another. This led to billions of dollars being spent on "entrenched warfare" that only benefitted a few and may have had little or no impact on the technical solution. Although those concerned with siting, designing, and constructing critical facilities should plan to address a number of issues, entrenched warfare can be avoided (see box next page).

The U.S. Geological Survey — Experiences in Site Evaluation

James Devine, then assistant director for engineering geology at the U.S. Geological Survey (USGS), described some of his and the USGS's experience in site evaluation for large engineering projects such as the TransAlaskan Pipeline System, the Teton Dam in Idaho, the proposed Skagit Nuclear Power Plant in Washington, and the Cape Thompson burial site (a legacy of the proposal to construct a harbor in Alaska using nuclear detonations). His main points follow.

- Conflicting concerns about the effects of melting permafrost and caribou migration resulted in much of the *TransAlaskan Pipeline System* being elevated along its 800-mile length. Although the solution substantially increased the cost and worried environmentalists, it has proven to be a good one during the 20 years of pipeline operations. Difficult and costly decisions can pay off in the long run.

- USGS scientists raised concerns about the integrity of the *Teton Dam*'s right abutment during earthquakes prior to the catastrophic failure of the dam at that location during its first filling in 1976. Although the failure was *not* due to an earthquake, there is some suspicion that sufficient attention to the scientists' concerns would have uncovered the design flaws that contributed to the failure. The

2 *A logic tree is a decision flow path, consisting of discrete nodes and branches, that allows the inclusion and weighing of different assumptions, models, and parameter values.*

Avoiding Entrenched Warfare

Plan For

- Out of control egos
- Vested interests and hidden agendas
- Jealous competition
- Arrogance and stonewalling
- Scientific and technical surprises
- Failure to consider social impacts of technical issues
- Adding extra conservatism at every step
- Ignoring facts and focusing on the desired outcome
- A provincial attitude that does not allow for independent review and oversight.

Strive For

- Open seeking of facts
- Mutual respect and trust, based on competence and integrity
- A multidisciplinary team
- Identification of issues that really make a difference
- Teamwork based on objectivity, anticipation of regulatory changes, flexibility, technical workshops, meetings, and publications to keep all interested parties informed
- An independent panel of experts to assist in decision making.

Source: Lloyd Cluff

report of these concerns was not acted upon because the USGS did not attach a sufficient sense of urgency to the report, as it was viewed only as a reconnaissance study, and the dam builder (the Bureau of Reclamation) was viewed as having an excellent record with respect to dams.

- The proposed *Skagit Nuclear Power Plant* was plagued by earthquake concerns. Issues were never resolved, and scientists became polarized into two camps over geologic issues. The science was viewed to be inadequately known for the purpose of siting a nuclear facility. As a result, the plant was never built, and the two camps remained bitterly split for years.

- Twenty-six millicuries of radioactive tracers were used to test a site for the proposed (and subsequently abandoned) plan to construct a harbor in Alaska using nuclear explosives. Thirty years after the nuclear material was buried in permafrost, some 20 miles from the nearest village, concerns were raised about the remaining two millicuries. In spite of the fact that there was no threat to humans or animals, the Department of Energy decided to remove all material that could have come in contact with the radioactive tracers. As a result, excessive attention was paid to something that was not a real risk; this encouraged the local population to assume that their health problems were caused by exposure to radioactivity and not other factors.

Licensing Hearings

Because licensing hearings can become a pivotal point in the site-assessment process's success or failure, the Board invited legal counsel from the NRC to provide whatever insight he might have that would help shed light on the licensing process. Lawrence Chandler, the NRC's assistant general counsel for hearings and enforcement, described his experience in nuclear power plant licensing hearings and presented a lawyer's perspective on scientific evidence. He made the following points.

- Although the licensing process may be long and costly, it works, and it has a demonstrated history of effectively resolving conflicts.

- The central issue is the credibility of the written and oral evidence presented. A witness's demeanor *is* part of this and has to be taken into account.

- Reasonable, not absolute, assurance is required. The standard of proof to demonstrate compliance with the regulations is "a preponderance of evidence."

- Quality assurance (in both a narrow and general sense) and its demonstration are important in determining whether evidence could be accepted.

Part 2: Common Issues in Site Assessment and Their Applicability to Yucca Mountain

The presentations and round-table discussion during the April meeting on site assessment of critical facilities identified 11 issues that appear to be directly relevant to the Yucca Mountain program; they are discussed below. The first two deal with strategic considerations in the technical arena, issues three through eight address some individual cross-cutting technical issues, and issues nine through eleven are of a nontechnical nature.

The DOE, in its effort to refocus and show progress in its civilian high-level radioactive waste management program, has developed a new program approach. As the Board has stated elsewhere, this new approach provides both opportunities and risks. One important opportunity recognized by the Board is the chance to make good use of the lessons learned by others during site assessment. The Board hopes that the DOE can benefit from the experiences of others and avoid some of their pitfalls while assessing the Yucca Mountain site.

Issue 1: Site Assessment — It Requires a Strategy

Based on the experience of others, site assessment is a lot more than a collection of data-gathering studies, tests, and analyses. Site assessment requires an iterative process that continually looks at the relationships among data-gathering, modeling, and performance assessment. Separating these elements into *sequential* rather than *parallel* efforts increases the possibility of unfocused and costly efforts that also can lead to serious problems at hearings.

With respect to Yucca Mountain, the 1988 Site Characterization Plan was more like a large menu of possible studies than a realizable, conceptually based, coherent strategy. The Board urged the OCRWM to embark on a strategy of priority setting through iterative performance assessment and also to encourage functional contact among data gatherers and modelers. In these areas the OCRWM has improved during the past few years, but it still has a way to go. In developing its new program approach, the OCRWM appears to have developed a strategy that includes prioritizing its activities with an eye toward the achievement of interim goals.

This new approach provides an important opportunity to streamline the scope and sequencing of site-characterization activities and to improve the technical rationale for deciding which studies shall be completed and which can be refined, abbreviated, or deleted. The Board applauds these aspects of the new approach. The Board does have some concerns, however, that excessive emphasis on completing schedules, such as reaching a site-suitability decision in 1998, could encourage decision making without an adequate and integrated database.

Issue 2: Determining Site Suitability and License Application — They also Require Strategies

Determining site suitability and applying for a license require more than presenting the results of individual scientific and technical studies and analyses; to succeed, the effort also requires a strategy. Although it was argued by some that the failure of the Martinsville site may have been due to the Illinois Siting Commission requiring zero release, the proponents of Martinsville may have failed the "standard" of demonstrating reasonable assurance through the presentation of a preponderance of evidence by highly credible witnesses. It was pointed out in the round-table discussion, following the presentations, that there did not appear to be an overall safety case (waste isolation strategy), merely a set of studies and analyses. The siting commission was largely left to fend for itself in determining how safe the disposal site would be.

With respect to Yucca Mountain, the lesson here is twofold. First, the DOE needs to develop a waste isolation strategy that provides a ready and comprehensible explanation of how the proposed repository will protect the public and the environment from the release of harmful radionuclides. Such a strategy has been developed and put to good use in Sweden. Second, the DOE must strive to present multiple lines of evidence that demonstrate reasonable assurance of a safe facility. Recently, for example, the DOE made its first attempt at resolving an issue (extreme erosion). The DOE submitted its report to the NRC, which after 15 months, rejected the report citing insufficient information. In the Board's view, this attempt was largely unsuccessful because there was too much emphasis on a controversial dating technique and not enough emphasis on other available evidence.

Issue 3: Uncertainties are Unavoidable

Scientific and technical uncertainties are unavoidable in site assessment and the design of critical facilities. The inability to address these uncertainties adequately was clearly a prime component in the rejection of the Martinsville site and the eventual abandonment of the Skagit Nuclear Power Plant site. At Martinsville, it was apparent that there were major differences of opinion between the applicant (Illinois Division of Nuclear Safety) and the Siting Commission as to what was an acceptable level of uncertainty.

The Yucca Mountain project seems to be aware of uncertainties, and the regulations are very explicit in not demanding absolute proof. The question remains, however, whether the DOE and the NRC agree sufficiently on what constitutes an acceptable level of uncertainty. If not clarified, significant problems, such as those in the Martinsville hearing, could surface during the licensing of Yucca Mountain, should it ever reach that stage. It is important that the DOE engage the NRC early to get a sense of what the NRC considers to be resolution of an issue. A good example of the potential to learn was the set of interactions between the NRC and the DOE on extreme erosion mentioned in Issue 2. The DOE would be well advised to evaluate what went wrong and apply any lessons learned to future attempts at issue resolution. (Also see discussion in Chapter 3 on resolving difficult issues.)

Issue 4: Expect Surprises

Surprises exist in any site investigation, particularly those that include underground investigations. As was pointed out, confidence about site and repository issues is highest at the beginning of detailed investigations.

This is a particularly critical issue with respect to Yucca Mountain. Although one cannot anticipate what specific surprises there may be, they will occur, and any long-term strategy and schedule should take the likelihood of their occurrence into account. The OCRWM's present schedule assumes that no major surprises will occur. Although underground exploration has begun, surface-based studies have already yielded the unanticipated. These include the unexpected width of the Ghost Dance fault zone, the discovery of the proposed Sundance fault, perched and other water in a number of drill holes, and evidence for a wetter pluvial climate in the past than originally had been suggested.

Issue 5: Technical and Institutional Overconfidence Does Not Pay

It became evident during the course of the presentations that technical and institutional overconfidence — which can lead to arrogance — does not pay; it can result in programmatic and physical failure as evidenced by the builder's refusal to back off from the initial design of the Auburn Dam in spite of the concern for faulting and the apparent lack of attention to details that eventually led to the failure of the Teton Dam.

It is too early to tell whether programmatic failure is around the corner at Yucca Mountain. A sense of overconfidence, however, may have already contributed to the DOE's long track record of failing to meet overly optimistic schedules, lack of contingency planning, and unfulfilled promises.

Issue 6: Independent Technical Review is Important

Independent technical review adds both quality and credibility. The lack of an independent technical review was an identified weakness in the Martinsville site assessment. Outside review made important contributions to the WIPP, the Auburn Dam, the New Melones Dam, and the Diablo Canyon Nuclear Power Plant in regard to both technical content and program credibility.

Although the Yucca Mountain project certainly has many outside oversight and review groups, its managers seem reluctant to use outside input in the decision-making process. An example of this is the rejection of the Board's suggestion to set up a geoengineering board to provide ongoing advice to managers and staff at the project level. This reluctance is not uniform throughout the whole program. Those involved in the volcanism effort, for example, appear very eager to solicit external expert judgment to help choose between competing hypotheses, and this is producing a payoff. (See discussion of how the DOE has handled the issue of volcanism in the following chapter.) Finally, the DOE is initiating a process by which panels associated with the National Academy of Sciences will review technical reports associated with the determination of site suitability.

Issue 7: Quality Assurance Counts

Quality assurance is serious business. Martinsville provides an example of how a breakdown of quality assurance in one area placed doubts on the whole program and was an important contributor to the Illinois Siting Commission's rejection of the site.

Quality assurance is one area where the DOE appears to have learned a valuable lesson. Progress, however, is not easy. In its review of the 1988 Site Characterization Plan, the NRC raised serious concerns about the DOE's quality assurance program. The DOE's initial response was to install a program that was so overbearing that scientists rebelled. New efforts by the DOE have made the process more logical and tolerable. However, problems in quality assurance related to the design of the exploratory studies facility indicate that continuing diligence is essential.

Issue 8: Regulations Must Be Clear

Although views differ as to the need for specificity, regulations must be clear. Those individuals at the meeting who commented on regulations agreed that clarity was essential for both applicant and regulator. Some felt that many of the problems at Martinsville could have been avoided had there been specific criteria to address issues such as uncertainty in ground-water models and the life of the waste container; those working on Gorleben are satisfied with the German approach of a simple systems standard (such as dose) and the inherent flexibility to make tradeoffs. There may not be a happy medium; different countries have different philosophies with respect to specificity of regulations.

In the case of Yucca Mountain, this issue is in a state of flux because of the review process initiated by the 1992 Energy Act. As of this writing, no one really knows what the National Academy of Sciences will conclude nor how the EPA and the NRC will react to the NAS recommendations. Clarity is of course a desired goal for any set of criteria. In its *First Report* (NWTRB 1990a), the Board pointed out confusion over the 300–1,000-year requirement of "substantially complete containment" in the NRC regulations. This was clarified by the NRC. A similar example of the need for further clarification is associated with the regulatory concept of "ground-water travel time." This is addressed in Chapter 4.

Lessons Learned

1. Site assessment is a lot more than a collection of data-gathering studies, tests, and analyses; it needs a strategy.

2. Site suitability and licensing require more than presenting the results of individual studies and analyses; they, too, require a strategy.

3. Scientific and technical uncertainties are unavoidable and have to be accounted for.

4. Expect surprises.

5. Technical and institutional overconfidence does not pay.

6. Independent technical review adds both quality and credibility.

7. Quality assurance counts.

8. Regulations have to be clear.

9. Political and institutional considerations are important.

10. Process counts.

11. Public involvement is necessary.

Issue 9: Political and Institutional Issues Count, Too

Whether scientists and engineers like it or not, political and institutional considerations are important. Political considerations are an integral part of waste disposal and many other critical technical issues. One of the participants went so far as to say that scientists and engineers should realize that siting waste facilities is not primarily technical and *cannot* be solved by primarily technical means. It is important to understand the role these different considerations play. Clearly, it is not "wrong" for the governor of Lower Saxony to reject a reprocessing plant for political reasons while recognizing that it can be operated safely, or for the government of Alberta to make the choice of Swan Hills over Ryley a political decision. It was wrong, however, according to the Illinois Siting Commission, to pick Martinsville as a low-level waste site for political reasons and pay insufficient attention to important safety issues.

With respect to Yucca Mountain, the lesson is that no one should expect any choice to necessarily be the "best" technical choice for the location of a high-level waste repository. Efforts should, instead, concentrate on whether the choice is an acceptable one. As the representative from the German nuclear waste program pointed out, *all* sites have flaws.

Issue 10: Process Counts

The NRC attorney underscored the central issue at a licensing hearing: the credibility of the written and oral evidence presented. As revealed in the Martinsville case, the demeanor of the witness (or *how* the evidence is presented) affects the witness's credibility and has to be taken into account. Although the substitution of technically, rather than legally, based review panels, such as for the Point Conception LNG site, may lead to greater emphasis on the purely technical content, it is not apparent that this approach will be applied elsewhere. Finally, the Board was informed that the success of the WIPP on technical issues in court battles was matched by a corresponding lack of success on procedural issues.

Thus far, the DOE generally has been successful in court on procedural issues relating to Yucca Mountain. However, it has not yet been involved in a licensing hearing on technical issues. The format for a licensing hearing has its own special requirements. The DOE will have to prepare itself for the demanding combination of law and science required by this process.

Issue 11: Public Involvement — It's Necessary

Public involvement is another of those process-oriented issues discussed by several speakers at the meeting. Although there was general agreement that public involvement is necessary, there was some divergence of views with respect to the extent and timing of this involvement and its desirability. Some participants placed great emphasis on this aspect; the discussion of the waste treatment facility in Alberta was largely devoted to the importance of meaningful and carefully planned public involvement. The perspective from the German participant, on the other hand, was more skeptical. This difference in views may be due to the individuals involved, specific experiences at respective sites, and cultural and philosophical differences.

In the case of Yucca Mountain, the Board has stressed the need for more meaningful public involvement before making major decisions. The DOE has held several stakeholder meetings and has proposed involving the public in the site-suitability determination process. If implemented, that proposal would represent progress in this area.

Recommendation

Much can be learned from past experience siting critical and other highly controversial facilities that is applicable to the Yucca Mountain program. The DOE *must* look more carefully than it has to date at these experiences and incorporate what has been learned into its strategy and planning.

Chapter 3
Resolving Difficult Issues — Volcanism

Introduction

In its tenth report (NWTRB 1994b), the Board addressed the resolution of difficult technical issues associated with siting a high-level waste repository at the proposed Yucca Mountain site. The Report concentrated on the problem of determining future climate and its impact on the isolation of high-level waste. In it, the Board recommended that a resolution strategy be formulated based on several components. These include: an understanding of how climate (or any other process or phenomenon under consideration) could cause the proposed repository to fail; an emphasis (in the case of future climate issues) on data over modeling; and the incorporation of outside expertise. It is also important that limitations on future scientific investigations (*When is enough, enough?*) be based primarily on the impact these investigations would have on assessing and demonstrating repository safety.

In this report, the Board addresses another such difficult issue, the impact of volcanism on the proposed repository at Yucca Mountain, the real progress being made toward its resolution, and those elements in the DOE's volcanism program that are facilitating this progress. Finally, a comparison is drawn with the DOE's seismic hazard program, which is proceeding at a slower pace and which could draw useful lessons from the approach taken in addressing volcanism.

Background on Volcanism

Yucca Mountain lies within a region that has experienced volcanism from the Miocene epoch to possibly as recently as the Holocene epoch (the past 10,000 years). During the mid-to-late Miocene epoch (approximately 16 million to 6 million years ago) major volcanic caldera-forming[1] eruptions and eruptions of ash flows occurred in the Yucca Mountain region; the proposed repository would be placed in these ash flows (tuffs). Major volcanic eruptions have not occurred in southern Nevada for more than 6 million years, and an eruption of this type is not regarded as a significant hazard to the repository. The focus of concern over volcanism is the potential for renewed volcanic eruptions or intrusions of a lesser magnitude in the immediate area of Yucca Mountain. During the last several million years, volcanic activity (small cinder cones, lava flows, and dikes) has been concentrated mostly in and around Crater Flat, an intermountain basin immediately west of Yucca Mountain. The most recent activity took place at the Lathrop Wells Volcanic Center (a single young cone), some 15 kilometers south-southwest from the proposed repository site.

The most consequential impact of volcanism would be the disruption of the repository by the formation of a new volcanic center directly under or immediately adjacent to the repository itself. Such an intrusion could result in the transport of harmful radionuclides directly to the land surface. Other more indirect concerns address the mechanical, ther-

1 *A caldera is a large, generally circular crater, formed by volcanic explosion and/or collapse, that is many times larger than the vents through which the volcanic material was brought to the surface.*

mal, and chemical effects of volcanic activity on the hydrologic regime, ground water being the primary path of concern by which radionuclides might reach the accessible environment.

The DOE's strategy has been to focus its initial studies on the assumed highly consequential direct disruption of the repository. The approach has been to use probabilistic methods to estimate the likelihood of such an occurrence and determine whether the probabilities are low enough that little additional effort on direct disruption is warranted. This topic would then be addressed in a *topical report*,[2] which would be submitted to the NRC. As this probabilistic effort reached its conclusion, increased attention would be paid to assessing the more indirect effects of volcanism.

Controversies

The Board, at meetings of its Panel on Structural Geology & Geoengineering, has observed several, often highly contentious, controversies that have arisen with respect to volcanism and the proposed repository. Most of these involve disputes between scientists associated with the primary DOE contractor on volcanism, Los Alamos National Laboratory (LANL), and individual scientists at the USGS, the NRC, the NRC-funded Center for Nuclear Waste Regulatory Analysis (CNWRA), the University of Nevada at Las Vegas (UNLV), and the state of Nevada. Controversies center around the following five issues.

1. *The age of most recent volcanism at Lathrop Wells.* This controversy revolves around the appropriateness and limitations of the different age-dating techniques used in geologic investigations. Some scientists at the USGS, relying on radiometric potassium-argon and argon-argon dating, have argued that the most recent volcanic activity near Yucca Mountain occurred about 140,000 years ago at the Lathrop Wells Volcanic Center. LANL scientists questioned the ability of the techniques to resolve dates during the last 100,000 years, citing scatter in the calculated age dates caused by so little radiogenic argon (needed to date the rocks) being produced by radioactive decay during that time period. Using several other techniques, including the extent of landform erosion, LANL scientists concluded that the most recent volcanic activity at Lathrop Wells could have been less than 20,000 years ago.

2. *The mode of volcanic activity*. This controversy is related to the age-dating controversy. Individual scientists at the USGS have argued that, based on paleomagnetic data and potassium-argon and argon-argon dating, the volcanic activity at Lathrop Wells has been *monogenetic*, that is, a single episode of eruptions from the same source closely spaced in time. LANL scientists, on the other hand, have maintained that there is strong evidence from their dates and geochemistry that some of the activity, particularly that at Lathrop Wells is *polycyclic*, that is, it consists of multiple eruptions over tens of thousands of years at the same location but from different magma sources.

3. *Structural control of past and future volcanic activity*. LANL scientists have argued that because volcanic activity has occurred primarily west of the repository in the Crater Flat Volcanic Zone, there is an extremely high likelihood that, if there were any volcanic activity in the Yucca Mountain region in the next 10,000 years, it would occur there again, particularly at Lathrop Wells. UNLV scientists maintain that, although most of the activity during the past 4 million years has occurred in the Crater Flat area, there also was some activity less than 3 million years ago at Buckboard Mesa, approximately 30 kilometers north of the proposed repository site. This, and the orientation of some faults in Crater Flat, suggests to the UNLV scientists that Yucca Mountain itself should be included in the zone of future volcanic activity.

2 *Topical reports traditionally have been employed in reactor licensing as a means of facilitating the review of hardware or analytical approaches frequently used by electric utilities in the construction of nuclear reactors. Once the topical report has been reviewed and accepted by the NRC staff, it then becomes a generic staff evaluation that can be referenced in subsequent individual reactor license reviews.*

4. *Probabilistic models of volcanic activity*. LANL scientists have proposed that the most appropriate approach to modeling future volcanic activity is to assume that this activity will occur randomly (i.e. unpredictably) in space and time within a given zone. Scientists at the UNLV and at the CNWRA have argued that complete unpredictability is not warranted, and temporal and spatial trends within zones must be examined to take into account systematic effects that might exist. The possibility should be reflected that volcanic activity waxes and wanes over time and that there is some spacial clustering.

5. *Sufficiency of data for reliable probabilistic estimates of volcanic hazard*. Some scientists associated with the state of Nevada and the NRC have questioned the reliability of probabilistic estimates of volcanic hazard based on existing data. LANL scientists, on the other hand, maintain that these estimates of hazard have not changed much in recent years and that there is little likelihood they will change as additional data are collected.

The Board's position on these controversies has been that they be viewed with respect to their potential effects on siting and building a safe repository. In the *Fourth Report* (NWTRB 1991b), the Board stated that a "structured probabilistic approach can not only serve to make useful estimates of volcanic hazard at Yucca Mountain, but also can help discriminate between those [controversies] that have a significant impact on volcanic hazard and those that do not." (p. 17)

At its most recent meeting on volcanism in March 1994, the Board was pleased to note that progress has been made on many of the above issues. LANL has conducted much additional work, particularly at the Lathrop Wells Volcanic Center. LANL scientists now point to four episodes of volcanic activity coming from a minimum of six to eight geochemically distinct magma batches. The most recent activity, restricted to minor ash deposits may have occurred as recently as 9,000 to 4,000 years ago. In the Board's view, the case for volcanism (polycyclic or not) extending into the Holocene epoch has been strengthened. It also appears that, based on the evaluation of volcanic ash found in some faults, there may be a link between volcanic activity and faulting in and around Crater Flat.

Disputes on the structural control of volcanism and differences in probabilistic models remain open, but revised calculations of the probability of direct intrusion into the repository are providing a good deal of insight on the effects of the different assumptions on these calculations. Although there is no mutually agreed upon single estimate, the range of the probabilistic estimates is on the order of one chance in 1,000 to one chance in 100,000 of a direct disruption of the repository in the next 10,000 years. Most of the estimates center about the one chance in 10,000 range, while structural and probabilistic models proposed by UNLV scientists yield higher probabilities. LANL scientists had suggested originally that they would recommend ceasing further studies on direct disruption if the probabilities could be shown to be less than one in 10,000.[3] They now believe that their range of estimates straddle this criterion and further studies are needed.

LANL scientists believe that the range of probabilistic estimates will not change in the future and have suggested initiation of a formally elicited expert judgment study to evaluate the different input assumptions and their effects on calculations. The Board strongly endorses this proposal, noting the importance of the direct inclusion of experts from outside of the DOE in conducting the study and providing the expertise. The identification of uncertainties, if any, that have a significant effect on the calculated probabilities of disruption of the repository, would provide a strong focus for future investigations.

NRC scientists at the Board's meeting supported the idea that the range of probabilistic estimates probably will not change very much; they endorsed the

3 *This criterion grew out of a statement in 40 CFR 191, the original EPA standard for high-level waste repositories. It was stated that categories of events or processes that are estimated to have less than one chance in 10,000 of occurring over 10,000 years need not be considered in repository performance assessment. In a process initiated by the Energy Policy Act of 1992, the EPA standard for Yucca Mountain is undergoing revision.*

idea of the expert judgment study; and they expressed the view that the NRC and the DOE were not as far apart as originally thought and, while not at closure, are moving toward consensus. Issues remain,[4] but in the Board's view progress has, indeed, been made.

Factors Leading Toward Successful Resolution

The Board believes it is important to point out those elements in the study of volcanism that appear to be accelerating progress toward successful resolution of the problem. Once identified, these elements, along with the insights developed as a result of the Board's analysis of the future climate issue in the tenth report (NWTRB 1994b), could be applied to many of the issues facing those charged with addressing whether a safe repository can be sited at Yucca Mountain. Elements in the study of volcanism that may be accelerating the problem-resolution process are discussed briefly below.

1. *Develop solid science.* No difficult scientific issue can be resolved without developing a solid scientific basis for addressing important questions. An impressive amount of high-quality research into volcanic issues has been carried out. Particular emphasis should be given to LANL's detailed mapping and trenching, its use of multiple techniques in age dating, and the incorporation of geochemical models to decipher the origin of particular volcanic sequences. Much of the work has been concentrated on the Lathrop Wells Volcanic Center. The UNLV also has made important contributions to our understanding, particularly at Black Cone and Red Cone in Crater Flat. The next big scientific push will be in geophysics, to confirm the limits of assumed volcanic activity. The DOE is evaluating that geophysical techniques can be the most useful.

2. *Make early and continuing efforts to define the important scientific questions.* Difficult issues can pose a bewildering array of questions that could be answered. Devoting too much time to unimportant questions and not enough time to important questions is an ever-present problem faced in large endeavors. In the case of direct volcanic disruption of the repository, the tool for separating the important from the less important has been the use of probabilistic estimates of direct repository disruption. For example, it appears that questions related to the age of most recent volcanic activity and monogenetic versus polycyclic volcanism are less important than questions related to structural control of future volcanic activity. It was recognized early on that data gathering and probabilistic calculations were not sequential operations but should be conducted in parallel to provide feedback. The early use of probabilistic calculations in an area where there has been relatively little previous experience has also widened the methodological foundation of these calculations and increased the confidence in their results.

3. *Engage critics, get feedback, and modify the approach.* There is always something to be learned from vigorous and meaningful exchanges between scientists with different perspectives on controversial issues. This has been most evident in the probabilistic studies of direct disruption of the repository. Scientists from LANL have been publishing the results of their calculations for more than 10 years. They have received much feedback, and their work has been affected by this feedback. For example, in March 1993 LANL circulated a preliminary draft version of the milestone report entitled *Status of Volcanic Hazard Studies for the Yucca Mountain Site Characterization Project* (LANL 1993). It received many critical comments and, as evidenced by the presentation at the Board's March 1994 meeting, many of those comments have been taken into account. Different conceptual models, based on real concerns, have been proposed by scientists from both the CNWRA and

4 *For example, scientists from both the UNLV and CNWRA have raised the possibility that a future eruption in the vicinity of Yucca Mountain could be Plinian in nature. This is a highly explosive mode of eruption, aided by the presence of water and other volatiles in the magma, with large volumes of ash and gas reaching great heights. It is argued that this type of eruption could disperse large amounts of harmful radionuclides if it went right through the repository. Although the DOE needs to address this issue, the Board has not seen any evidence to support the contention that this would be a likely scenario at Yucca Mountain.*

the UNLV. Although sometimes appearing overly defensive, the LANL scientists have acknowledged the validity of these concerns.

4. *Recognize the need for the systematic inclusion of outside expert judgment*. The Board consistently has emphasized the need for the DOE to seek external expertise outside of its own contractors. Although the LANL scientists have recognized that there are different views with respect to how one calculates probabilities and what parameters one uses in these calculations, they have, until now, attempted to use their own analysts to capture these views. Whereas this may be acceptable in certain situations, on highly controversial issues and where standardized calculations are not the norm, better ways may exist. It is preferable to involve the outside parties directly along with knowledgeable independent scientists and, if possible, use independent analysts to integrate the views and perform the calculations. This technique has been used successfully in estimating earthquake hazard at nuclear power plants in the eastern United States, a subject of great controversy among seismologists. It also has been applied successfully to Yucca Mountain in a demonstration project by the Electric Power Research Institute (EPRI) that assessed fault-displacement hazard at the proposed repository (EPRI 1993). The DOE has recognized the need to use this type of study to help resolve volcanic issues at Yucca Mountain. Aside from increasing the quality of any calculations and conclusions, such a study can do a great deal to increase their credibility among skeptical scientists, regulators, and the public.

Conclusions

Although some questions remain and additional work on volcanism needs to be done, particularly in the assessment of the effects of volcanism on the hydrologic regime, progress has been made toward resolution of this difficult issue. Some individual technical topics are close to technical resolution and the range of probabilistic estimates of direct disruption are not expected to change much in the future. Much of the progress that has been achieved has resulted from an aggressive approach by the DOE and its contractor LANL. They have built a foundation of solid scientific work; they have made early and continuing efforts to define important issues through the use of probability; they have engaged their critics, received feedback, and modified their assessments; and they have recognized the importance of outside experts in assessing and confirming their probabilistic calculations and conclusions.

There has been some indication that the DOE may defer resolution of volcanism-related issues at the Yucca Mountain project. The Board believes, however, that the DOE would be well advised to maintain the momentum that has developed and has been recognized by outside bodies, including this Board.

This is not to say that there will be no surprises. Indeed, the previously mentioned revision of the EPA standard could affect the conclusions of the probabilistic study. A decision to increase the period of performance from the previously assumed 10,000 years would undoubtedly increase the risk. The DOE should conduct sensitivity studies (as it has in other fields) to start assessing the effects of this and other possible changes.

Postscript on Seismic Hazard

The rate of progress in seismic hazard estimation is not as encouraging as it has been with respect to volcanism. Although the DOE's contractors (mainly the USGS) have been conducting high-quality field investigations and are reaching important conclusions, the deferral of most hazard calculations has delayed progress. The approach here has been more sequential than parallel. Many of the insights to be gained from detailed probabilistic hazard estimates are not available.[5] Instead of doing the actual calculations, the DOE has chosen to submit a topical report on seismic hazard methodology. In contrast to volcanism, there is a wealth of experience in probabilistic seismic hazard estimation. The critical issue with respect to probabilistic seismic hazard estima-

5 *The previously mentioned EPRI study on fault displacement hazard is a good example of the kind of work that can provide useful insights.*

tion is not so much methodology, but rather how it is used.

The Board believes that those responsible for seismic hazard evaluation for the Yucca Mountain project could learn much from the approach taken by their project colleagues responsible for volcanic hazard estimation.

Recommendations

1. The DOE should capitalize on the progress demonstrated in resolving volcanism-related issues at Yucca Mountain. It should proceed with the elicitation of outside expertise and maintain momentum in resolving this issue.

2. The DOE should reevaluate its approach to seismic hazard estimation and place more emphasis on probabilistic hazard estimates and the insights they can provide to guiding the field investigations and resolution of important questions.

Chapter 4
Panel Activities, Conclusions, and Recommendations

Geoengineering

Since the publication of the Board's tenth report (NWTRB 1994b), the OCRWM's program has continued to evolve. On October 1, 1994, program management announced the formal adoption of the proposed program approach. As a result of this program restructuring, some site-characterization activities have been deferred, abbreviated, or deleted. Current emphasis in the program is focused on activities to support what the DOE is calling a "technical" site-suitability determination by 1998. The OCRWM is looking at site suitability as a three-step process: (1) In 1998 a decision will be made about the suitability of the site from a technical and scientific perspective; this is being called "technical" site suitability.[1] (2) If the site is found suitable, in 2000 after evaluating environmental, transportation, and socioeconomic issues through the development of an environmental impact statement (EIS) for the proposed repository, the Secretary of Energy would recommend the site to the President for development as a repository. (3) If approved, the DOE would then submit in 2001 an application to the Nuclear Regulatory Commission for a license to begin repository construction.

The Board has heard a number of presentations on the new program approach, and, although many details remain unclear, the Board sent a letter to the OCRWM director on December 6, 1994, outlining the Board's views on the scope of exploration and testing activities it considers necessary to support a technically defensible evaluation of site suitability. (See Appendix G.)

In the Board's view, under *ideal* circumstances sufficient time may be available to complete all the excavation activities identified in the letter before the 1998 decision. However, given existing management issues within the OCRWM program (turnover at the management level, large numbers of geographically dispersed employees and subcontractors, high overhead, contract and procurement practices), the Board underscored in its letter its concern that completing all the activities within the next four years, even with the planned increases in the OCRWM's operating budget after fiscal year 1995, could pose a significant challenge to management. Even if all of the data could be collected, data must be assembled and interpreted over longer time periods. In its letter, the Board emphasized the need for careful planning and efficient use of resources.

As a result of Board and panel activities,[2] this section of the report: (1) addresses what the Board believes to be the important elements of the DOE's evolving waste isolation strategy, (2) explains some aspects of

1 Unless otherwise indicated, the term "site-suitability decision" as used in this report refers to the DOE's 1998 "technical" site-suitability decision.

2 In June 1994, the Board held a meeting of the Panel on Structural Geology & Geoengineering in Las Vegas; Board member Edward Cording and staff met with the DOE staff and contractors and visited Yucca Mountain in August and again in December 1994. In November 1994, this panel held a joint meeting with the Panel on Hydrogeology & Geochemistry in Washington, D.C.

what the Board outlined in its December letter to be the *minimum suite* of exploration and testing activities (and their rationales) required to determine site suitability, (3) proposes ways to perform the defined exploration and associated testing efficiently,[3] and (4) addresses the DOE's current approach to thermal management of spent nuclear fuel in the repository program.

The DOE's Evolving Waste Isolation Strategy

The Board has long advocated that the DOE reevaluate its exploration and testing program to focus the program on those tests and studies that will provide data essential to assessing site suitability (NWTRB 1990b p.16.). Although a key element in the new program approach is to set priorities, further progress is needed in developing and describing a coherent waste isolation strategy. This strategy would provide a basis for prioritizing surface-based and subsurface exploration and testing activities; it also would establish a plan for exploration and testing as well as for repository design and development that the technical and lay communities can understand. Since the Board's first meeting with the DOE in 1989, elements of a waste isolation strategy have been evolving, some of which the Board strongly supports. With the restructuring brought about by the new program approach, it is critical that this process continue and that the DOE articulate what the waste isolation strategy entails and what major changes to this strategy will be made.

The DOE appears to be moving toward more reliance on both natural *and* engineered barriers, which together will limit the movement of radionuclides from the repository to the accessible environment. Use of both kinds of barriers gives the repository system a degree of redundancy because different barriers are not likely to respond in the same way to processes and events. It is important to note, however, that engineered and natural barriers are not completely independent; engineered barriers reside within an environment formed by the natural barriers. Therefore, to be able to predict the performance of the engineered barriers, one must understand the potential behavior of the natural barriers under the changing conditions that will be created by emplacing heat-generating spent nuclear fuel in a repository.

To gain an understanding of the Yucca Mountain geology, the DOE planned a balanced program of surface-based testing and underground exploration and testing. Surface-based testing has been under way at the site for the last several years. Surface mapping and surface-based drilling are important, but the recently initiated underground tunneling will provide access to structures to enable program personnel to locate, observe, and test known and previously unknown features such as joints, faults, and bedding over significant distances. It is particularly important to use horizontal exploration to locate and then test the hydrologic and geochemical characteristics in and adjacent to faults and joints. Because most of these features are predominantly *near vertical, north-south trending*, it is very difficult, if not impossible, to characterize them using surface-based drilling alone.

The DOE designed its exploration and testing plan based on major studies conducted in 1991 (SNL 1991, DOE 1991). It concluded at that time that the site requires significant exploration and testing *above, at*, and *below* the proposed repository level. As a result, the DOE adopted the multilevel exploratory facility configuration. Enhancements to this configuration resulted in the exploratory facility that was current prior to the changes initiated by the new program approach.

Under the DOE's new program approach, the exploration and testing program emphasizes those investigations and engineering activities the DOE believes are necessary and sufficient to support the 1998 site-suitability determination; these activities will be emphasized during fiscal years 1995 through 1997. Other exploration and associated testing will be deferred; ultimately, some may be eliminated.

3 *"Associated testing" refers to testing that is conducted in conjunction with or immediately subsequent to excavation of the exploratory studies facility.*

As the program approach evolved during the summer of 1994, the amount of exploration and testing to be deferred increased appreciably, apparently not to meet the needs of an articulated waste isolation strategy, but as a result of budget and schedule limitations. The Board believes that a minimum suite of underground exploration and associated testing is required before making a defensive site-suitability determination, to provide a sound technical basis for the decision, and to ensure that no major surprises will be encountered later when the deferred exploration and testing are completed. The activities recommended by the Board (see following discussion on exploration and testing) differ somewhat (especially in timing) from some of the DOE's recently proposed plans; they are consistent with the need to execute the exploration and associated testing in a cost-effective and timely manner.

Underground Excavation and Testing

The Board believes that substantially more underground excavation will be needed than the DOE currently plans before the 1998 date for the site-suitability decision. Sufficient underground exploration is needed to (1) confirm at repository depth the continuity and orientation of structures already identified by surface investigations, (2) to identify structures not evident at the surface, and (3) to permit testing of structures and formations to determine their significance for long-term waste isolation. The influence of geologic structures and formations on the hydrologic properties of the repository block is the primary issue of concern. To the extent that faults serve as potentially fast flow paths or may be capable of large displacement following waste emplacement, determination of an appropriate offset distance for waste emplacement may be necessary.

Specifically, the Board believes that the following excavation is needed for a "technical" site-suitability determination.

- As now planned, excavate the North Ramp to the repository level and excavate a "main drift" through the center of the repository block in an approximately north-south direction parallel to and just west of the Ghost Dance fault zone.[4]

North Ramp excavation will allow conditions to be observed in stratigraphic units above the repository level. Once the 25-ft-diameter tunnel boring machine has traversed through the central portion of the repository, a decision can be made to either stop the tunnel boring machine or continue to drive it out the South Ramp. The decision should be based on the progress and efficiency that is being achieved with the large machine and the ability to complete high priority tests and side drifts off the main tunnel *while* the large machine continues its drive.

Information important for site suitability that should be gathered during this first traverse includes: (1) data from examination, mapping, and testing in the Topopah Spring welded tuff, the formation in which the repository is to be sited; (2) data from the excavation and testing of rock samples and possibly free water obtained along the traverse; and (3) isotopic testing for the presence of chlorine-36, tritium, or carbon-14 to help identify the presence of fast-flow paths through the formation.

- Explore faults and structures in the central portion of the repository block east of the main drift.

The planned intersection of the Ghost Dance fault at two locations with small-diameter drifts is appropriate. An eastern extension of one of these drifts is needed to fully cross the Ghost Dance fault zone. Further extension of the drift into the Imbricate fault as far as the eastern boundary of the block may be needed unless adequate information about the Imbricate fault can be obtained from the North Ramp.

- Explore faults and structures in the repository block to the *west* of the main drift, particularly in

4 *The completion of this tunnel excavation should be feasible in fiscal year 1995, assuming: (1) programmatic delays to tunnel boring machine operations are avoided or minimized and (2) a highly mobile machine capable of mechanically excavating test alcoves is obtained.*

the area of fracturing and suspected faulting identified by Scott and Bonk (Scott et al. 1984).

Most of the proposed repository area is located to the west of the main drift, and at least one tunnel is needed in the area of suspected faulting extending west to the Solitario Canyon fault to evaluate the suitability of that portion of the repository horizon.

- Excavate into the Calico Hills formation from a portal separate from the existing North Portal.

This excavation should cross the Ghost Dance fault zone at least once at a location immediately below one of the crossings at the Topopah Spring formation level.

Exploration of the Calico Hills formation is a high-priority activity. Under the new program approach, the DOE plans to wait until the Ghost Dance fault has been explored before making a decision on the need to explore the Calico Hills formation. The DOE apparently has decided that data on the Calico Hills formation geologic features are not needed to support a site-suitability determination or even a site recommendation. The planned decision about excavating the Calico Hills is based on planning and equipment acquisition lead times rather than on the need for important data. In the Board's view, the Calico Hills formation is a major feature at the site; its characteristics must be known if site suitability is to be determined. It may prove especially critical if the DOE continues with its current plans to use a "low" thermal management strategy. (See discussion below on thermal loading of a repository.)

During the June 13-14, 1994, panel meeting, the merits of de-coupling the access to the Calico Hills formation from the main level of the exploratory facility were discussed (the Board had suggested this option on several occasions). This could be accomplished by excavating into the Calico Hills formation from a new portal located south of the geologic block. Using this approach would (1) eliminate the need to interface with activities in the main tunnel at the repository depth, (2) avoid, potentially, some of the quality assurance and other constraints necessary when excavating in the repository operational area, (3) reduce the estimated cost of construction by approximately $100 million,[5] and (4) perhaps most important, permit the consideration of a competitive, fixed-price contract for construction of this exploratory tunnel. The winning construction contractor could provide all construction equipment, including a tunnel boring machine.

The Thermal Test Area

Thermal testing should be initiated as soon as possible, consistent with the excavation schedule and other exploration priorities. The tests should emphasize evaluation of thermal-hydrologic behavior over the range of thermal loadings that are being considered. The Board considers appropriate DOE's plan to eliminate the complex of intersecting drifts known as the core test area and to conduct tests at specific areas where data need to be obtained in the underground exploratory facility.

Recently, the DOE has considered placing the thermal tests off the North Ramp above the repository level, in a stratigraphic unit different from the one in which the repository would be located. However, the Board considers that the most appropriate location for thermal test drifts would be at the repository level, in the rock type in which repository emplacement drifts would be excavated. To permit an early start of thermal tests at the repository level, it is suggested that efforts be made to speed excavation of the North Ramp, procure tunneling equipment required for the thermal test area, and continue to coordinate testing and construction efforts to minimize interference and take advantage of the improvements that can be made in the excavation schedule.

5 *In 1992, the DOE estimated that the Calico Hills facility built in conjunction with other portions of the ESF would cost approximately $130 million. The DOE presentation on June 14, 1994, estimated the cost for a de-coupled access to the Calico Hills to be approximately $30 million.*

It would be desirable to use a small-diameter tunnel boring machine to excavate thermal test drifts at repository level (rather than drill-and-blast technology) to most closely simulate the rock wall conditions influencing stress and fracture conditions that would exist in the repository emplacement drifts. Consideration should be given to combining the development of the test drift with the westward extension of a drift across the repository block. The two might be accomplished with a single setup of a tunnel boring machine off the bottom of the North Ramp.

Procurement procedures, such as leasing or use of contractor-supplied equipment, should be considered. Such a machine could be rapidly set up for use in driving these and other drifts, such as east-west extensions that cross the Ghost Dance and other faults in the central part of the repository block.

The DOE's New Program Approach to Managing the Thermal Loading of a Repository

The DOE's program approach to thermal management is built around the following three elements: (1) the development of flexible designs for the repository and waste package; (2) a technical site-suitability determination, site recommendation to the President, and, if approved, a license application to construct assuming that the repository will be operated at a "low" thermal loading; and (3) long-term testing to support a possible license update in 2008 to a high thermal-loading strategy.

The "flexible" design for the repository would accommodate a range of areal mass loadings that are being considered; the thermal characteristics of the waste could be adjusted by waste acceptance and storage (i.e., ageing) options. A repository design for the primary area at a "low" thermal strategy is to be used for a license application to construct.[6] A license application update would be submitted to the NRC by 2008 either to maintain the "low" thermal management strategy and greatly expand the repository area (to be able to accommodate the entire 70,000 metric tons of spent fuel and high-level waste) or to convert to a high thermal management strategy that would allow all of the waste to be placed in the primary area of the Yucca Mountain geologic block. The DOE plans to evaluate waste acceptance and storage options as well as what thermal testing will be needed for the "low" thermal-loading scenario prior to making a site-suitability determination. If the application later is to be converted to a higher strategy, then specific thermal test data to support the revised application would be required. It is expected that long-term testing would be an integral part of the program for either option.

The Board has often raised questions about the thermal testing requirements for both site suitability and license application and whether these requirements can be achieved in view of the tight schedule. At the Board's November meeting on thermal management, the DOE presented a description of the proposed high thermal tests and an anticipated schedule. If the schedule is maintained, only data from the large block test will be available before 1998 and a two-year accelerated in-situ test prior to site recommendation and the construction license application. Long-term heater tests will be continued between the license application and the possible license update in 2008. A primary focus of these early tests is the thermo-mechanical response and other thermal properties of the tuff. Because this testing will not be performed at drift or mountain scale, it is doubtful that these early experiments will answer the important questions raised about the thermo-hydrological response of the mountain.

The DOE currently believes that the best possibility for a successful license application may lie with a "low" thermal-loading strategy. This belief rests on the belief that it will be easier to provide bounding and confirmatory analyses on the response of the geologic system to very "low" thermal loads, which are closer to ambient conditions at the site. The strategy can be formally stated that the areal power density for the repository will be less than some value X

6 *The assumption is that the primary area consists of regions east and west of the Ghost Dance fault; however, this has not yet been firmly decided by the DOE nor supported by adequate underground exploration.*

(kW / acre), where X is yet unknown but will be sufficiently small such that it can be argued with reasonable assurance to have a minimal and predictable disturbance on mountain scale processes.

The predictability of this strategy is very important. First it implies that the thermo-hydrological effects can be predicted or bounded for a "low" thermal-loading scenario (this is essential for defining the disturbed zone and computing travel times and for total performance assessment). This belief is based in part on the fact that the amount, flux, and refluxing of mobilized liquid and vapor water increases as the thermal load increases.

It should be emphasized that the DOE's strategy is not based on any belief that, given the current state of knowledge, the "low" thermal load is better or has inherent long-term waste isolation advantages over say, an extended-dry thermal strategy, but that there is a higher probability of achieving regulatory compliance with this strategy by 2001 than with any other strategy.

The Topopah Spring formation in which the repository is to be located is an unsaturated welded tuff with a porosity of approximately 15 percent. About two-thirds of the rock-pore volume contains water. There is a general consensus that over most of the repository block the rock matrix is in approximate hydrologic equilibrium, with a downward water flux in the range of 0.01 to 0.1 mm per year balanced by an upward water vapor flux driven by the natural geothermal gradient. Surface water infiltration does not appear significant, except for episodic infiltration that may occur along faults or other major fractures.

Three distinct repository thermal management strategies have emerged as viable alternatives: the "low" option, sometimes referred to as the minimum disturbance option, and two "high" options, the SCP revised concept (large in-drift waste packages) and a high concept tailored to keep repository temperatures above boiling for as long as possible, referred to as the extended-dry concept.

The "Low" thermal management option

In theory, the "low" thermal management concept would allow as little heat into the repository host rock as is reasonably achievable given the requirement to dispose of heat-producing waste. The heat would be minimized by selectively ageing the fuel prior to emplacement and by a low areal density of the waste packages. The DOE has not yet developed a comprehensive concept, or rationale, for this concept of what would constitute a reasonably achievable, minimum thermal loading (kW / acre). Concepts have been discussed that attempt to limit rock temperatures to about 60°C (25° above ambient), in a non-backfilled drift. However, selective waste package ageing would be required, and a repository area of the order of 3,000 acres — about twice the size of the current repository block — would be needed.

It has been postulated that ventilation concepts that continuously remove warm moist air from the repository over the entire preclosure period (i.e., now 100 years) could appreciably reduce the required area. This concept has not yet been evaluated by the DOE, and at this point is speculative because it has not been established that sufficient water can be mobilized from the rock to provide the required latent heat transfer. Testing is needed to validate this concept.

The "low" strategy has a number of *perceived* benefits: (1) Only ambient and some near-ambient test data may be needed for analysis, potentially making it a fast concept to implement, since high-temperature testing would not be required. (2) The ambient hydrology would be disturbed only minimally, and less rock matrix water would be mobilized than for other concepts. (3) "Low" temperatures could be more compatible with the use of backfill, allowing it to be considered for hydraulic isolation, geochemical buffering, or sorption. (4) Near-ambient conditions should minimize geochemical changes in the host rock, possibly allowing a large amount of thermodynamic data collected at ambient temperatures to be used. (5) Minimizing rock temperatures would lead to greater long-term tunnel stability. In addition, if the waste packages are self-shielding, the "low" thermal concept might allow unprotected human access for observation, monitoring, and maintenance prior to repository closure.

The strategy also has a number of *perceived* and real disadvantages: (1) Significantly more acreage would be required if the anticipated 70,000 metric tons of spent fuel and high-level waste is to be placed in the repository. The additional area would have to have a high probability of being found acceptable before choosing the strategy and be characterized *prior* to expanding the repository area, leading to greater cost and time to implement this concept. (2) To develop adequate confidence in the "low" thermal strategy, the DOE must first provide evidence that ambient conditions are adequate for long-term waste isolation, then determine how temperatures tens of degrees greater than ambient could affect the waste isolation capacity of a repository. It has been postulated that a few tens of degrees greater than ambient may have profound effects on water movement and distribution below, at, and above the repository horizon, including possible seepage into the repository. (3) Metal corrosion is increasingly aggressive at greater than about 60°C and 70 percent relative humidity — conditions that may be difficult to avoid with the "low" concept. This means that under the "low" concept greater emphasis would have to be placed on geologic barriers, particularly the Calico Hills formation below the repository horizon. (4) Ageing and fuel receipt management may not be sufficient to offset the effects of using large waste packages (i.e., multipurpose canisters containing 21 assemblies from pressurized water reactors) without the packages creating pockets with temperatures above boiling, which could allow water to migrate toward the cooler waste packages.

Despite programmatic emphasis on the "low" thermal management strategy, all of the thermal tests described at the November meeting focused on high-temperature thermal / mechanical / hydrological interactions. No consideration has been given to what data are needed, or the tests necessary to obtain the data, for the "low" scenario. All DOE efforts to date have concentrated on high-temperature scenarios. Data requirements for license application to construct a repository with a "low" thermal loading have been neglected so far.

There are as yet a number of details that must be addressed before this strategy, and underlying assumptions, can be evaluated adequately. There must be a nexus between the waste isolation strategy and the thermal management strategy. The dependence on geologic barriers, such as the Calico Hills formation, may well be a dominant factor in evaluating the DOE's "low" thermal-loading option. Thermal testing and modeling efforts need to be planned to provide technical bases for the developing strategies.

It has not yet been determined what data are needed, how they will be used, how they will be obtained by 2001, and how minimal and predictable disturbance will be defined and demonstrated.

Finally, alternatives need to be provided for implementing the program approach should it prove impossible to make a case to amend the license for a high thermal loading by 2008. It is the Board's understanding that the DOE is in the process developing a strategy for characterizing the expansion areas that would be required to accommodate the 70,000 metric tons of spent fuel and high-level waste should the "low" thermal-loading strategy become the preferred strategy.

Management Concerns

For the project to move efficiently toward an early site-suitability determination and successful license application, traditional DOE management practices may not be sufficient. Aggressive management will be required to reduce high program costs and slow rates of progress, for example, by avoiding lengthy equipment acquisitions and employing contractual practices that encourage contractor incentives and accountability. Far better integration and communication among personnel in management, engineering, construction, quality assurance, and science will be required.

Finally, as is common on such first-of-a-kind, large underground construction projects, the OCRWM should establish a geoengineering board of expert consultants with experience in the engineering, construction, and management of large underground projects.[7] This board would work with the technical and management staff and report to Yucca Mountain project management; the experts could meet regularly with Yucca Mountain project management, staff, and contractors to review detailed issues early on — *when they are first being considered.* A standing geoengineering board also would give the DOE quick access, when necessary, to expert consultants who are familiar with the technology and the project. Potential members should be nationally recognized and selected based on experience serving on similar boards for projects of commensurate complexity.

Conclusions

1. Exploration and testing priorities for determining site suitability have not been established. Articulating a waste isolation strategy will help the DOE identify these priorities.

2. The DOE's current schedule and budget have resulted in a reduction of underground exploration and testing. The Board believes a minimal suite of underground exploration and testing will be required prior to determining site suitability in 1998 to ensure that no surprises are encountered later during further exploration and, if the site is found suitable, during repository construction.

3. The program approach to thermal management is preliminary and has not been developed sufficiently to allow its evaluation. The strategy assumes that the areal power density for the repository, as yet undefined, will be sufficiently small such that it can be argued to have a minimal and predictable disturbance on the mountain. The strategy is not based on any belief that a "low" thermal load is better than other strategies or has inherent advantages for waste isolation over another strategy. It is based on the present belief that there is a higher probability of achieving regulatory compliance with this strategy given the current state of knowledge of site processes and the potential response of those processes to increased temperatures.

4. A number of details still must be addressed before this strategy, and its underlying assumptions, can be evaluated adequately. There must be a nexus between the waste isolation and the thermal management strategies. The dependence on geologic barriers, such as the Calico Hills formation, may well be a dominant factor in evaluating the DOE's "low" thermal-loading option, given the corrosion environment created by lower temperatures and the consequent need to rely more on the natural barrier.

5. A most important issue is the need to identify the thermal test data that will be used to support the license application. At present, no information exists on what data are needed, how they will be used, how they will be obtained by 2001, and how minimal and predictable disturbance will be defined and demonstrated.

6. Common to all thermal management options is the need to understand the efficiencies that could result from continuing to ventilate the repository after emplacement and prior to closure. It has been postulated that the removal of moist air from the repository could be very beneficial to the "low" options and possibly for operational considerations.

Recommendations

1. The DOE must articulate a clear waste isolation strategy that provides an understandable technical rationale for prioritizing the studies to be completed under the new program approach.

2. The Board recommends that the DOE carry out the minimum suite of underground exploration and associated testing outlined in its December 6, 1994, letter *prior* to the site-suitability decision to ensure that no major surprises will be encountered during the completion of the deferred program.

3. The DOE should develop a more efficient approach to managing the design and construction of the underground exploratory facility; this approach should include the creation of a geoengineering board of expert consultants and greater account-

7 *The Board recommended this in its October 1993 report on underground exploration and testing (NWTRB 1993b).*

ability and incentives for cost-effective and timely performance of the contractors.[8]

4. The DOE should clarify the “low” thermal management strategy and its relation to the overall waste isolation strategy for the repository. Data needed to support this concept should be defined and the means of obtaining the data determined. For the program approach to be credible, the DOE also must clearly define actions that will be taken if a case *cannot* be made for a high thermal loading during a license amendment prior to 2008.

Tectonic Features and Processes

Volcanism

Volcanism and the related volcanic hazard have been associated with highly controversial issues at Yucca Mountain. In the past year, there has been evidence that meaningful progress is being made toward their resolution. This is the subject of a special chapter in this report entitled “Resolving Difficult Issues—Volcanism” (see Chapter 3).

Faulting and Earthquakes

For many years, the Ghost Dance fault has been known to extend directly through the projected repository block, with total cumulative displacements of up to several tens of meters. Much concern has been expressed regarding the possibility of the fault being an avenue for fast ground-water transport. From the point of view of faulting and earthquakes, however, the concern with the Ghost Dance fault has been not so much with the possibility of its producing earthquakes and the associated ground shaking, but instead with the *fault displacements* that might disrupt the integrity of canisters buried within the repository. Thus the degree of activity of the Ghost Dance fault, as well as its precise location and degree of branching, have long been a subject of concern and study. If the fault were found to be “inactive” (i.e., not having broken in many thousands of years), then it might be possible to dismiss it and its branches as sources of possible offsets within the repository. The presence of active faults, however, could limit the amount of repository area available for disposal.

With the encouragement of the Board, a recent intensive field study of the Ghost Dance fault was carried out by a team of geologists led by the USGS mapping the zone with great precision at the very detailed scale of 1:240. One important discovery was that the fault was not a single break, but instead consisted of a number of individual breaks distributed over a zone about 200 meters wide at the land surface. Although the presence of branch fractures had been identified in earlier studies, the total width of the zone came as somewhat of a surprise. The largest displacement was clearly on the main trace near the center of the zone, and the branches were characterized by relatively small displacements and were not necessarily continuous. If the fault and its various branches eventually should be deemed active, then the presence of faults scattered throughout the wide zone — if also present at repository depth — would create a more serious problem to canister integrity, and possibly to the total usable repository volume, than had previously been anticipated.

In this light, members of the Board urged the USGS to make an even greater effort to find convincing evidence of Ghost Dance fault zone activity or nonactivity. It was recommended that localities where young datable alluvium might be present be searched carefully to determine if their displacement or nondisplacement could be used to demonstrate the degree of fault activity, that is, whether or not displacements had taken place on it within relatively recent geologic time. Most of the identified fault trace lies on Yucca Mountain so that alluvial cover is not as abundant as on faults bordering the mountain block. Some of these bordering faults have been shown to have recent displacements, while such displacements can be precluded on others. This neotectonic work is still under way.

8 See the Board’s ESF report (NWTRB 1993b).

In the meantime, continuing detailed, systematic, geologic mapping of the Ghost Dance fault by the USGS-led team revealed another potentially significant surprise: It appeared to the team that the north-trending Ghost Dance fault may be dextrally offset some 60 meters by a northwest-trending fault, termed the Sundance fault. If this were to be true, it would have potentially important implications; the proposed Sundance fault would then clearly be the younger of the two faults, and the Ghost Dance fault and its branches could possibly be considered inactive. This would be because 60 meters of cumulative displacement would have to represent many repeated earthquakes over a long period of time, and if the Ghost Dance fault itself had not broken during this same period, a relatively permanent change in the faulting pattern must have taken place subsequent to the time of the last displacement on the Ghost Dance fault. Furthermore, there was a suggestion that the proposed Sundance fault and other northwest-trending faults parallel to it were truncated by the active north-trending faults bordering Yucca Mountain on both the west and east. Thus, convincing geologic evidence possibly might be found that could dismiss *both* the Ghost Dance and the proposed Sundance faults, as well as their branches, as sources of potential fault displacement during the repository's projected life, and therefore eliminate at least one important repository design issue.

The geologic evidence for the offset of the Ghost Dance fault by the proposed Sundance fault was admittedly, somewhat interpretive because (1) it was based on the apparent offset of volcanic units with very subtle stratigraphic markers, (2) it required as-yet-undemonstrated continuity of the Ghost Dance branches and their relative positions, and (3) because much of the critical outcrop area is overlain by large patches of colluvium and talus. One USGS geologist who was not involved earlier in this particular mapping program reviewed the field evidence independently and concluded that the evidence for offset was unconvincing. The possible offset of the Ghost Dance fault by the proposed Sundance fault was considered by the USGS to be such a critical issue, however, that the USGS then called in as consultants seven geologists, none of whom had been involved in this particular mapping effort and two of whom are exterior to the USGS. They spent 2-1/2 days in the field and several additional days reviewing the maps and associated documents, as well as preparing individual letter reports.

The resulting consultants' independent reports did not conclusively support one side or the other on the issue of whether the proposed Sundance fault offsets the Ghost Dance fault. None of the consultants doubted the existence of the Ghost Dance fault, but many doubts remained about the nature of the proposed Sundance fault and even its existence as a throughgoing fault of significant displacement. In the intersection area between the two faults — in Split Wash north of Antler Ridge — so much talus and colluvial cover are present that none of the consultants felt that the suggested offset could be demonstrated with real confidence, at least not at this time. The offset represented a reasonable interpretation to some.

The Board believes that the suggested offset of the Ghost Dance fault by the proposed Sundance fault is not sufficiently well demonstrated at the present time to declare the Ghost Dance fault effectively inactive. To what extent further field work, such as excavating a "pavement" of full exposure in the intersection area, is justified now to clarify the relationship depends, at least in part, on how critical the issue of fault offset is to demonstrating site suitability, in keeping with DOE's new program approach. Much depends, not least in part, on how the waste packages are to be placed in the repository. Displacement on the main trace Ghost Dance fault probably can be readily accommodated simply by applying a reasonable setback of waste packages from the fault. But the many branch faults within a wide zone, if also present at depth, may pose a more difficult problem in that markedly less area may be available for disposal. If, as is presently planned, the waste packages will be drift-emplaced, then sufficient freeboard (waste-package/drift wall spacing) probably can be established to accommodate minor fault offset (e.g., 10 cm) without compromising waste package integrity, although this may depend on the nature of the backfill, if any. However, waste packages must also be emplaced with sufficiently rigid supports so that they will not "roll around" during the shaking of the earthquakes that undoubtedly will occur at the repository during its projected life of at least 10,000 years. Accommodating possible fault offset at the same time as guaranteeing stability during earthquake shaking represents an interesting engineering challenge. In the Board's opinion, these issues must be faced in determining the degree of priority to be placed on further studies of the Ghost Dance-Sundance fault intersection. In the meantime, it is possible (and hopeful) that neotectonic studies of one or both faults may resolve the issue of degree of activity independently, thus making the intersection problem effectively irrelevant.

It is important to recognize that, although some of the geometric relations between the Ghost Dance fault and the proposed Sundance fault eventually may be exposed underground, if the tunnel should intersect the two faults at precisely the right location, the problem is essentially one of viewing the faults in plan view, because of the proposed strike-slip displacement. It is likely that surface-based studies will be much more revealing in this regard than the necessarily limited underground exposures.

Based on currently completed detailed geologic mapping, it is unclear what the geometric relationship is between the Ghost Dance fault and the proposed Sundance fault (i.e., which is the younger). The Ghost Dance fault, however, still appears to be the more continuous and significant fault. The Board recommends that, for issues such as repository design, the DOE continue to consider the Ghost Dance fault "active" and capable of fault displacements within the repository block (as is demonstrably true of some nearby parallel faults outside of the block), at least until such time as contravening evidence becomes available.

On the broader subject of repository seismic hazard assessment, Chapter 3 points out that progress in this area has not been as encouraging as has been that in volcanic hazard assessment. A principal reason, in the Board's opinion, is that most seismic hazard calculations have been delayed until completion of the field work, whereas the volcanic hazard analyses have been carried out in tandem with the field research, so that there has been constant iteration and constant reevaluation of research priorities. For a more extensive discussion, the reader is referred to Chapter 3. Recommendation 2, below, is repeated from that Section.

Recommendations

1. Until contravening evidence becomes available, the DOE should continue to assume that the Ghost Dance fault is "active" and capable of fault displacement within the repository block.

2. The DOE should reevaluate its approach to seismic hazard estimation and place more emphasis on probabilistic hazard estimates and the insights they can provide to guiding the field investigations and resolution of important questions.

Hydrogeology and Geochemistry

Hydrogeology and geochemistry are central to any determination of site suitability and prediction of repository performance. The amount and geochemistry of the water that might reach the proposed repository to corrode waste containers and transport radionuclides to the accessible environment are issues critical to radioactive waste isolation. The Board continues to believe that characterization of Yucca Mountain hydrology and geochemistry is fundamental to site-suitability determination. Key areas of research reviewed at Board meetings during 1994 include: (1) the hydrology of the unsaturated and saturated zones on April 11-12 in Reno, Nevada; and (2) radionuclide transport on July 12-13 in Denver, Colorado. In addition, the Board's Panel on Hydrogeology & Geochemistry reviewed the groundwater travel time issue on September 12-13, in Las Vegas, Nevada, and jointly sponsored a meeting with the Panel on Structural Geology & Geoengineering on thermal management strategies on November 17-18 in Washington, D.C. The following are the main conclusions from those meetings.

Radionuclide Transport

On July 12, 1994, in Denver, Colorado, the Board convened a meeting on radionuclide transport at Yucca Mountain. Presentations were given by representatives of the OCRWM, the national laboratories, and management and operations (M&O) consultants. Presentations were also given by a representative of the NRC and an independent group working on innovative engineered barriers.

The organization of the technical presentations was loosely based on a "top-down" approach, well suited for the information-gathering purpose of the meeting. This approach uses the results of total system performance assessments (TSPA) to judge the relative importance of processes and helps to focus discussion on outstanding issues to be debated and resolved. If systematically applied, a "top-down" TSPA approach guides and limits data collection and identifies and prioritizes processes and parameters with the greatest impact on repository safety.

Suggestions and recommendations stemming from the meeting are organized in the following narrative under the headings (1) TSPA models, (2) sorption, (3) colloids, (4) engineered barrier system performance, and (5) unsaturated zone flow and transport.

TSPA models

The role of expert judgment in TSPA models needs to be recognized and examined as it critically affects determining site suitability in 1998. The Board is interested in how the DOE proposes to quantify expert judgments and other subjective information within TSPAs. This topic was discussed in some detail in the Board's tenth report (NWTRB 1994b).

The strategy of applying TSPA to guide and constrain data collection was cited at the meeting, but no clear examples of its use by the OCRWM were provided. For instance, the Board wanted to know how the DOE is using the results of TSPA to drive data collection and to converge on establishing site suitability in 1998. (See the discussion on the use of TSPA in the section on risk and performance analysis in this chapter.)

The M&O made presentations on those factors that are most important for repository safety as a function of time (10,000, 100,000, and 1,000,000 years). Although insightful, it remains unclear to the Board, however, how these results are being used to influence decisions on safety compliance and design issues.

Sorption

The minimum K_d strategy[9] based on bounding analysis to identify a limited number of radionuclides for further study is a rational and cost-effective approach. The general principles of this approach should be applied to guide and constrain other areas of data collection and model development related to radionuclide migration, notably colloid studies and flow and transport models for the near and far field.

If a peak-dose standard for safety is adopted, long-lived nonsolubility-limited and weakly adsorbed nuclides (e.g., selenium, technetium, iodine) are consequential. These nuclides may be importantly retarded by diffusion from fractures into the tuff matrix. The role of such matrix diffusion to slow and dampen nuclide releases needs to be evaluated.

The in-growth of daughter radionuclides during far-field migration of parent nuclides (e.g., uranium-235) was shown in a recent TSPA (SNL 1994) to affect radionuclide releases to the accessible environment. It was not evident that such results were being used to identify the need for sorption studies of potentially important daughter elements.

The program at Yucca Mountain has begun using an ultracentrifuge apparatus to generate sorption data on tuffs under controlled, partially saturated conditions. The intent is to requalify previous batch sorption measurements made under saturated conditions for use in future TSPAs. Assuming favorable technical and cost considerations, the Board endorses the use of the ultracentrifuge technique for

9 *K_d is a measure of the capacity of a radionuclide in solution to adsorb on a solid surface: K_d = (amount adsorbed per weight of sorbent)/(amount in solution). K_d is also related to the degree to which this element will be retarded with respect to the advecting fluid: K_d=0 implies no adsorption and thus no retardation (i.e., the radionuclide moves with the average velocity of the fluid). A "minimum K_d strategy" is an approach to establishing research priorities for sorption studies. In brief, radionuclides that display values of K_d larger than 100 ml/g are ignored from further study (Meijer 1992). With a K_d value of 100 ml/g a radionuclide moves only 0.1 to 0.25 percent as fast as the ground water (Freeze et al., 1979). More mobile (less adsorbed) radionuclides (e.g., uranium, neptunium, selenium, technetium, iodine, and carbon) have lower K_d values and are retained for further study in TSPA.*

the limited set of future sorption measurements that are found necessary.

Colloids

A negative finding about the potential formation, stability, or transport of colloids in any region of the repository may be sufficient reason for dismissing their possible importance for the transport of radionuclides. The current strategy is to define and examine questions in series regarding the formation, stability, and transport of colloids. Instead, questions should be framed for examination in parallel, such that the answer to a single question may eliminate colloids as a concern. Two such parallel questions that could be considered are: (a) Are colloids unable to migrate across the different unsaturated-zone backfills in proposed EBS designs and (b) are radionuclides reversibly adsorbed to colloids? If specific nuclides are reversibly adsorbed by colloids, they will tend to desorb from colloidal surfaces onto much more abundant adjacent rock surfaces in transport and so be retarded, dispersed and diluted. “Yes” answers to either or both of these questions thus would eliminate colloidal transport as a waste isolation issue.

It seems unlikely that significant colloidal transport of radionuclides could occur except of those that are irreversibly adsorbed on colloids if the colloids can escape the engineered barrier system and are transported to the water table by episodic fracture flow. This possibility would need to be evaluated only if answers to both previous questions were found to be “no”.

Engineered barrier system performance

Presentations and discussion at the July Board meeting showed that radionuclide-transport models in the most recently published TSPAs sponsored by the DOE (SNL 1994 and Intera 1994) are still rudimentary and lack detail. This is not consistent with the level of detail of modeling radionuclide transport in the engineered barrier system in the programs of most other countries with nuclear waste disposal programs nor with the increased emphasis on the engineered barrier system in this country under the new program approach. Improvement in TSPA models for radionuclide transport, sorption, and solubility is needed. The Board understands (and agrees with the decision) that the DOE has decided to give greater attention to these areas.

The timing and concentration of releases of radionuclides from the engineered barrier system to the natural barriers of a repository depend strongly on the distribution of waste-package failures as a function of time. The estimation in the most recent TSPAs of waste-package failure distributions using rudimentary corrosion models was a significant improvement over that used in prior total system performance assessments. However, much improvement in the waste-package failure distribution models is still needed. Since the waste package is an engineered, rather than a natural, system, it will have a finite useful lifetime for retarding and containing radionuclides. If the period of regulatory concern extends significantly beyond this lifetime, the importance of the contribution of the waste package to long-term repository performance will lessen.

Knowledge of radionuclide solubilities is necessary to model their transport, and the DOE is carrying out radionuclide-solubility research to extend the current state of such knowledge. Unfortunately, this research is not linked as closely as it should be to other DOE-sponsored research on the dissolution rate of radioactive waste forms. Such linkage (e.g., by comparing solubility limits from the solubility research with solution concentrations from the waste-form dissolution-rate research) could help bracket the range of concentrations for radioelements. It could also assist in identifying dissolution kinetics or alteration-product metastability issues that typify low-temperature (<100°C) reactions in nature.

In general, diffusive transport is orders of magnitude slower than advective transport and therefore contributes more to repository performance. Which transport mechanism, diffusive or advective, dominates for transport of radionuclides in the engineered barrier system is a very complex issue. Among other things, it depends on the design of the engineered barrier system. For example, if filler within the waste package and backfill outside the waste package are not used — seemingly the DOE’s preferred engineered barrier system design at the moment — then advective transport may dominate.

Fillers and backfill may cause diffusive transport to dominate, and, therefore, the Board urges the DOE to study their use.

Unsaturated zone flow and transport

The perched water in zones beneath the proposed repository horizon represents a weighted mixture of historic recharge that has moved through Yucca Mountain matrix and via episodic fracture flow. Chemical and isotopic analyses of such perched waters should receive high priority with the goal of estimating/bounding the ages and proportions of the perched water that have derived from matrix and fractures. These analyses might provide some indication of the relative importance of these flow mechanisms to waste isolation and ground-water travel time. Of particular interest would be information that clarifies whether the pathway for the perched water passes through the repository horizon or comes laterally below it.

Current and planned flow and transport models for Yucca Mountain are acknowledged to be quite complex, with the possibility that model predictions will always differ significantly from field observations. The Board recommends that a bounding analysis approach for modeling flow and transport in the far field also be considered. In this approach, the demonstration of compliance with safety criteria should be emphasized, rather than a complete understanding of complex fluid flow and transport throughout Yucca Mountain which can, in all reality, never be demonstrated.

Matrix diffusion was shown in the one recent TSPA (Intera 1994) to be a potentially important process affecting radionuclide migration in the far field. In particular, matrix diffusion would act to reduce the peak dose rates of long-lived, nonsolubility-limited, weakly adsorbed radionuclides such as selenium-79, technetium-99, iodine-129. The DOE needs to better quantify the role of matrix diffusion in limiting the release of these radionuclides to the accessible environment.

Ground-Water Travel Time

On September 12-13, 1994, the Board's Panel on Hydrogeology & Geochemistry met in Las Vegas, Nevada, to hear about the DOE's proposed approach to the ground-water travel time[10] (GWTT) regulations. In addition, the Board hoped to review the historical background of related regulations, hear about the details of the DOE's proposed approach, and receive comments from the NRC and affected government units on their views of the regulations and the DOE's approach. Following are several insights and perspectives gained during this meeting.

The ability of the natural system to isolate waste, independent of any engineered barriers, is an important element in a safety argument and is vital for public acceptance. There is also general agreement about the intimate relationship between the hydrogeology of a site and the site's ability to isolate waste. For these reasons, the NRC established regulations on ground-water travel time to provide a "simple" way to evaluate the performance of the natural system. This performance measure (originally formulated to choose among prospective sites) addresses the site's hydrogeology and is in addition to the total system performance requirements.

The framework for making a technical assessment of the suitability of Yucca Mountain to serve as the location of a high-level radioactive waste repository is contained in 10 CFR 960, the DOE's General Guidelines for the Recommendation of Sites for Nuclear Waste Repositories. The key disqualifying condition in the guidelines with respect to the site's hydrogeology is 10 CFR 960.4-2-1:

> *A site shall be disqualified if the pre-waste-emplacement ground-water travel time from the disturbed zone to the accessible environment is expected to be less than 1,000 years along any pathway of likely and significant radionuclide travel.*

10 *Ground-water travel time, as defined by the NRC, is the time it takes ground water to travel from the edge of the "disturbed zone" to the accessible environment. "Disturbed zone" is a poorly understood concept.*

NRC regulation 10 CFR 60.113(a)(2) is expressed in the following performance objective for the site's hydrogeology:

> *The geologic repository shall be located so that pre-waste-emplacement ground-water travel time along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment shall be at least 1,000 years or such other travel time as may be approved or specified by the Commission.*

For various reasons, the regulations have not achieved their intended objectives, that is, of being a simple(r) measure of the site's ability to isolate waste. The primary problem is that the ambiguities in the current criteria have led to widely varying interpretations. Several ambiguities are particularly important to note because, based on the current language in DOE's guidelines, they constitute opportunities for disqualifying or qualifying the site merely through their interpretation.

Computation and interpretation of ground-water travel time

Ground-water travel time is a key regulatory concept. Yet from a physical viewpoint it is a poorly defined concept, making its measurement and computation non-unique and subject to multiple interpretations. There is some disagreement on which transport processes (advection, velocity dispersion, molecular diffusion, etc.) should be included in the computation. Also, the computation is quite sensitive to the conceptual model that is adopted for the unsaturated zone hydrogeology. Ground-water travel times computed via different conceptual models can be significantly different.

In addition, a consensus about the interpretation, and thus the size, of the "disturbed" zone has been lacking. Certain interpretations assume that the "disturbed" zone includes the whole rock volume that is affected by repository heat. In this case if the thermal load is very large, the disturbed zone potentially can extend into the water table, eliminating the long travel times expected through the unsaturated zone and making the 1,000-year standard of 10 CFR 60 or 10 CFR 960 difficult to satisfy. Such an interpretation would also imply that a thermal management strategy would have to be specified before a disturbed zone could be defined. The NRC provided the following interpretation of the "disturbed zone" during the recent NRC / DOE technical exchange on ground-water travel time held in Denver, Colorado, on Nov. 29-Dec. 1, 1994:

> *The purpose of evaluating ground-water travel time from the "disturbed zone" to the accessible environment, rather than from the location of the underground facility to the accessible environment, was to preclude the NRC from making a compliance decision based on pre-existing GWTT that could be significantly decreased as a result of repository construction and the effects of emplaced waste. In other words if the pre-emplacement GWTTs are faster than the post-emplacement travel times (both computed from the repository or some boundary external to the repository), then the disturbed zone is essentially the repository itself or that external boundary.*[11]

Thus the "disturbed zone" is not simply the volume of rock that is heated, but the volume of rock that experiences adverse effects on the travel times due to the repository heat. This interpretation clearly emphasizes that a sound analysis and prediction of thermal-hydrological effects on ground-water travel time will be necessary in the DOE's license application.

Because the Yucca Mountain site is quite heterogeneous and the potential repository of finite extent, a distribution of travel times and not a single value will be calculated. The key issue then becomes how should computed travel times less than 1,000 years be interpreted. At one extreme, the state of Nevada argues that any evidence of any pathway with a travel time less than 1,000 years (independent of the magnitude of radionuclides transported by the path)

11 *Jeffrey Pohle, the NRC/DOE technical exchange on fracture flow and ground-water travel time, Denver, Colorado, November 29-December 1, 1994.*

constitutes a disqualifying condition. The NRC has proposed[12] taking the fastest travel time from each of the computed travel time distributions (a distribution is computed for each of the assumed geologic realizations/assumptions of the hydrological parameters) and comparing this set of fastest times to the 1,000-year standard. If the mean of the set of fastest travel times is greater than 1,000 years, then the qualifying condition is satisfied.

It is important to note that the fastest computed travel times are least constrained by data, have the greatest percentage of uncertainty, and are most model dependent. This is especially true for a highly heterogeneous medium such as the Yucca Mountain site where the anticipated travel time distribution could be very broad. The Board notes that the interpretations suggested by the state of Nevada and the NRC do not acknowledge the key issue, which is the travel time of significant concentrations of radionuclides, which could be considerably longer than the fastest path of ground-water flow. In contrast, the DOE's proposed approach discussed below will weight the travel times of various paths based on their ability to transport radionuclides.

The Board has other concerns with the notion that only the fastest computed travel time of each distribution would be used in comparisons to the 1,000-year standard. The fastest time(s) are least bound by data, very model dependent, and thus easily challenged as to their realism. In addition, the 1,000-year standard itself is somewhat arbitrary and without a sound technical basis. In the Board's view, a regulatory decision as important as site qualification/disqualification should be based on assumptions that are strongly supported by site-specific data and reasonable model computations/interpretations relevant to radionuclide transport that can be understood without undue difficulty by interested groups.

The DOE working group on ground-water travel time has provided a detailed outline of its proposed computational approach to addressing the regulations. Its schedule anticipates reaching a high-level finding on this issue in time for a DOE technical site-suitability determination in 1998. However, the highly technical nature of the computations and the compact schedule for carrying out the preliminary computations, then acquiring the relevant data and going through several iterations and reviews, suggests that completion of this work by the end of 1997 is somewhat optimistic.

Measurement of ground-water travel time

Because of the strong focus on the computation of ground-water travel time, there is a critical need for measurements that indicate the rate of deep water infiltration at Yucca Mountain. As part of the site-characterization effort, ground-water travel time is determined indirectly. In practice, the technique used is to analyze the composition of a sample of ground water for its chemical and isotopic constituents and then use a model to compute how long it took this water to arrive at its present composition since entering the subsurface.

When infiltrating the ground, surface waters contain an initial concentration of atmospheric radionuclides, which could be of cosmogenic origin or due to nuclear testing in the early 1950s. An ideal application of this technique occurs when a radioisotope of known concentration enters the subsurface in solution. If there are no other sources or sinks of this isotope in the subsurface, then knowledge of the half-life[13] and concentrations of this isotope (and/or daughter products[14]) allows an accurate computation of the subsurface "residence time." The most commonly used isotopes for the purposes of "dating" ground water at Yucca Mountain are tritium (^{3}H, half-life = 12.3 years), carbon-14 (^{14}C, half-life = 5,730 years), and chlorine-36 (^{36}Cl, half-life = 301,000 years). The interpretation of the "residence times" can be greatly obscured by numerous subsurface sources and sinks (e.g., through rock-water interac-

12 The NRC/DOE technical exchange on fracture flow and ground-water travel time, Denver, Colorado, November 29 - December 1, 1994.

13 "Half-life" is the time it takes for a given amount of radioactive isotope to decay to half of its original amount.

14 Isotopes that result from radioactive decay are called "daughter products."

tions) of the various isotopes, the mixing of waters of different residence times, and the fact that carbon-14 can move as gaseous carbon dioxide as well as in dissolved carbonate species.

Present radioisotope data clearly indicate a heterogeneous flow system in the unsaturated zone at the Yucca Mountain site with some potentially very "fast paths" that allow the rapid infiltration of water to significant depths, in the process bypassing waters with much longer subsurface residence times.[15] These data also indicate that fracture flow and lateral flows in the Calico Hills and other bedded units *might strongly influence or even dominate* the hydrologic system at Yucca Mountain. Present data only indicate that some water flows very rapidly through the mountain, probably during extreme climatic events. Some of this flow could take place laterally within formations from their outcrops in Solitario Canyon. Researchers are not yet capable of resolving the amounts, frequency, and sources of such recharge. A more comprehensive set (spatially) of isotopically determined dates may help to answer such questions and decide on the significance of these fast pathways to radionuclide transport from a potential repository.

Pneumatic Pathways

The state of Nevada and the other affected units of local government believe that predisturbance pneumatic (gas) pathways are a significant site-characterization issue. In addition, they believe that there is a conflict between the surface-based testing program and the scheduled excavation of the underground exploratory facility. These concerns were summarized and discussed at a scientific workshop held January 26 and 27, 1994, in Las Vegas, Nevada.

The Paintbrush nonwelded tuff unit (PTn) is significantly less permeable than the overlying Tiva Canyon unit and the underlying highly fractured Topopah Spring unit. Some feel that tunneling through the Ptn during the construction of the underground exploratory facility would short-circuit the PTn, dramatically perturbing the gas flow through the mountain. The projected start-up of the tunnel boring machine at the time of the workshop was fall 1994. Key concerns with this potential alteration of the pneumatic pathways articulated by the state of Nevada and the affected units of local government are bulleted and discussed below.

- Those concerned believe that the continuity of the pneumatic pathways would be changed irreversibly by the excavation of the exploratory studies facility, and the opportunity to fully characterize the *unperturbed* pneumatic pathways would be irretrievably lost.

Data collected prior to and after excavation would allow the changes in pneumatic continuity of the PTn formation to be delineated. There have been some measurements of the vertical permeability of the PTn formation to air by monitoring the pressure response at depth in stemmed or packed-off intervals in open boreholes as barometric pressure changes at land surface. Pressure responses have been analyzed for two sites to infer the vertical permeability of the PTn unit to air.[16] These measurements support the assumption that under natural conditions, the lower welded unit (the Topopah Spring member) is isolated to a fair degree, from the overlying Tiva Canyon member by the PTn.

The DOE has implemented an accelerated surface-based testing plan.[17] The intent of the accelerated program is to collect pneumatic data continuously during and after the exploratory studies facility con-

15 Al Yang (USGS) has reported measurements of bomb-pulse tritium in the Calico Hills formation with an estimated "residence time" of 32-36 years in the subsurface. ACNW Working Group Meeting on the Use of Isotopic Dating Methods, Las Vegas, NV, October 21, 1994.

16 This work was described by Ed Weeks of the USGS at the Scientific Round-Table on Yucca Mountain Pneumatic Continuity workshop in Las Vegas held January 26-27, 1994.

17 The DOE presented an Accelerated Surface Based Testing Plan on three occasions: at an NRC/DOE Technical Exchange held October 4-5, 1993; at a NWTRB meeting held October 19-20, 1993; and at the Scientific Round-Table on Yucca Mountain Pneumatic Continuity held January 26-27, 1994.

struction. These data are to provide complementary information on postdisturbance pneumatic continuity.[18]

Although the accelerated testing plan is progressing, it appears that the details of the plan had not been articulated clearly to the various parties.[19] During the Board's panel meeting on ground-water travel time, the DOE stated that this program is in progress and that the instrumentation in boreholes NRG-6 and NRG-7a will have been completed prior to the winter season, when the main barometric variations take place.[20] In view of the fact that the start of the TBM has been delayed from the projected date, the DOE accelerated program will benefit from the additional time for data collection.

- Those concerned believe that alteration of the preferential gas pathways due to excavation would interfere with some geochemical data interpretation.

Gas chemistry measurements can provide useful information for site characterization. Interpretation of gas chemistry data is based on the hypothesis that water samples collected from just below the water table that show chemical signatures in agreement with the adjacent gas chemistry imply slow diffuse recharge of waters. On the other hand, waters that showed significantly different chemical signatures compared to the adjacent gas chemistry would imply that the waters were derived from rapid-focused recharge.[21] The assertion is that short-circuiting the PTn potentially could allow rapid gas flow through the mountain, changing the in-situ gas chemistry and making this type of interpretation impossible. Some suggest that the mountain already has been perturbed by the surface drilling program and several of the open wells (UZ6) which penetrate the PTn.

- Those concerned wonder if it will be possible to select an optimal thermal load without undisturbed pneumatic continuity data.

Higher thermal-loading scenarios are expected to generate considerable vapor transport through large volumes of the mountain. This particular concern raises the question whether it will be possible to model the thermal response at Yucca Mountain without adequate information about the pneumatic continuity of the PTn unit.[22] Current performance assessment calculations cannot resolve differences between the performance of different thermal-loading strategies and do not indicate that a thermal management strategy will depend critically on any assumptions concerning pneumatic continuity of the PTn unit.[23] It should be noted that these computations are preliminary, depend strongly on the corrosion models being used, and do not take into complete account the effects of thermo-hydrology.

18 *It should be noted that the pneumatic pathways through the mountain would be significantly altered after the ESF and proposed repository are excavated.*

19 *Letter dated July 12, 1994, to Dr. Daniel Dreyfus from Les Bradshaw (Nye County, Nevada) requesting a written description of the YMSCO's accelerated surface-based testing program, which incorporates information concerning specific items raised in the letter.*

20 *The pneumatic data collection began in these two wells during November 1994. Initial results were presented at the NRC/DOE technical exchange at Denver, Colorado, on November 29-December 1, 1994.*

21 *Among the isotopes, carbon-14 moves as dissolved carbonate species in the ground water and also as gaseous carbon dioxide. Thus, relatively young carbon-14 ages at depth can help identify pneumatic pathways and suggest their importance. Such information should continue to be available from the carbon-14 dating of ground-water samples collected carefully from the ESF. Both gaseous carbon dioxide and dissolved carbonate species have been dated at Yucca Mountain using carbon-14. Because carbon dioxide gas moves faster than infiltrating ground water, the gas is younger based on carbon-14 analysis. However, exchange with older ground water dilutes the carbon-14 in carbon dioxide gas so that ages of gases determined by carbon-14 dating are older than their true ages. In other words, gaseous carbon dioxide in Yucca Mountain is younger than its age as established by carbon-14 age dating. Thus, gas ages determined by carbon-14 dating indicate maximum travel times of gases via unknown pathways to their sample locations at depth.*

22 *It is expected that vapor flow including released gaseous carbon-14, would be preferentially transported through these pathways to the external environment. For a discussion of the origin of carbon-14, see NWTRB 10th report (NWTRB 1994b): Radionuclide releases from spent fuel, p. 36. For a discussion of carbon-14 and its effect on performance, see section on risk and performance analysis in this chapter.*

23 *See section on risk and performance analysis in this chapter.*

In addition to the mountainwide pneumatic pathways, knowledge of the hydraulic properties at all length scales, from core-scale permeabilities to mountainwide flow pathways, is an important element of site characterization. A program for determining in-situ air permeability data (effective sample measurement scales in the range of 10 meters) was carried out by the USGS in 1994 to complement core measurements. These data show surprisingly small variations in the measured air permeability throughout the Topopah Spring, implying a fairly good fracture connectivity through this unit.

The Board agrees that the DOE's accelerated program to achieve adequate pneumatic pathways characterization should be articulated clearly and the required work completed within the projected time table. Specific details as to the number of wells, their location, instrumentation, and testing plans should be provided.

Surface-based dry drilling and testing and exploration and testing in the *underground* exploratory facility are the two major components of the DOE's site-characterization project at Yucca Mountain. It is apparent that some of the pneumatic pathways characterization (pre-ESF) conflicts with proposed underground activities. But the primary issue is to what degree, or for how long, should the undisturbed pneumatic pathways be characterized at the expense of the construction and exploration of the underground exploratory facility.

Conclusions

1. The Board believes that an early resolution by the NRC and DOE of the key ambiguities of the regulations governing ground-water travel time is essential before significant time and effort has been expended on ground-water travel time computations. A primary concern to the Board is that the DOE may allocate considerable resources to an elaborate, technically complex computation based on insufficient data concerning water movement. Because of the technical nature of the calculations and inherent uncertainties in computational models and interpretations, there is a very high probability that the travel time issue will not be resolved decisively to the satisfaction of the various stakeholders through this effort.

Although far from perfect, the isotopic data provide primary evidence of ground-water "residence times" at Yucca Mountain and the existence of fast paths for water flow. It is imperative that the DOE acquire a spatially more comprehensive data set of ground-water "residence times" in support of a conceptual flow model for Yucca Mountain. The present, limited data set has been obtained by analysis of a fraction of the samples previously collected from available wells. Most of the yet-to-be analyzed samples have been in storage for more than a year. There is an urgent need for isotopic analyses of the remaining stored samples. It is also important that the DOE continue the related effort of correcting and improving the accuracy of ground-water age-dates. Radioisotopic analysis of ground waters encountered in the exploratory studies facility in coming years should further improve the DOE's understanding of ground-water flow paths at Yucca Mountain.

2. The Board has recognized and stated in its previous reports[24] that there is considerable knowledge to be gained through underground exploration; the Board has encouraged the DOE to proceed expeditiously with the construction of the exploratory facility.[25] The accelerated plans for pneumatic testing scheduled through this winter season will provide sufficient data that will be useful in setting some baseline for pneumatic continuity.

Recommendations

1. The DOE working group on ground-water travel time should attempt to establish as early as possible the conceptual model of the unsaturated zone hydrology that it will use in the computation, so that

24 See NWTRB 1994b and NWTRB 1993b.

25 For a discussion of key tests needed in the underground facility see Appendix G.

the specific data requirements can be met at the earliest possible moment. In particular, the effort in isotopic data collection and analysis for ground-water age dating should be accelerated and expanded to increase the spatial resolution.

2. Because of the importance of the data that will be gained during underground excavation and because of the significant costs that would be incurred by further delays in construction, the Board recommends that construction of the exploratory facility not be delayed any further.

The Engineered Barrier System

The discussion in this section addresses four aspects of a repository engineered barrier system (EBS): (1) design of the waste package, (2) design of EBS components outside the waste package, (3) performance assessment and corrosion research, and (4) the defense wastes that eventually will be disposed of in a repository. After a brief review of the background, each of the four topics will be discussed in detail.

Waste Package Design

The DOE is moving ahead rapidly to implement its "focused MGDS development" approach.[26] DOE personnel discussed this approach briefly in presentations during the January and April 1994 full Board meetings and during a meeting of the Board's Panel on the Engineered Barrier System in March 1994. "Focused MGDS development" implies, *first*, setting now, by assumption if necessary, all requirements and technical parameters necessary to perform repository and waste package design, and *second*, moving forward with a single design for the repository and a single design for the waste package, carrying along with those designs only a limited number of repository / waste package subsystem alternatives important to waste isolation. According to the plan, the designs and their underlying parameters and assumptions will be validated using design analysis and evaluation, tradeoff studies, and / or laboratory work. If necessary, the designs will be modified. The potential advantage of this new approach is that it could result in completed repository and waste package designs in less time and with the expenditures of fewer resources than the previous approach.

Although not at all unusual during the preliminary design of a major project in the process industry, this approach departs considerably from the DOE's earlier planned approach. Previously, the DOE had planned to develop — at least for the waste package — several (six or seven) designs, then gradually reduce the number to one or two "winners" using a systematic analysis process.

Two big risks in this new approach are (1) that it may result in less than optimal designs, and, (2) if the assumptions now being made turn out to be wrong, a great deal of time and money will have been wasted.

A vital part of the "focused MGDS development" approach is the new "Controlled Design Assumption" (CDA) Document issued in late June 1994 (DOE 1994c). It is a precursor of a document that eventually will contain hundreds of the design parameters and assumptions necessary to proceed with the design of the waste package. Examples of a few of the many key assumptions in the CDA document include the following:

1. Waste packages shall be placed horizontally in drifts.

2. Rail shall be used for all underground transport of waste packages.

3. The NRC will grant burnup credit for criticality control for disposal.

4. The period of concern for criticality control shall be 10,000 years.

5. Waste packages shall *not* be shielded to nearby personnel limits but shall be shielded sufficiently to avoid radiation-enhanced corrosion.

26 MGDS stands for mined geologic disposal system, i.e., a repository.

6. The repository shall be designed for up to 100-year retrievability following emplacement initiation.

7. The fraction of waste packages breached at 1,000 years after closure shall be less than 1 percent, and the mean waste package lifetime shall be well in excess of 1,000 years.

8. The repository configuration shall be able to accommodate both a “high” thermal load (91-114kW/acre) and a “low” thermal load (28-40kW/acre). Waste package designs shall accommodate both thermal loads.

9. Performance confirmation areas shall be designed for both “high” and “low” thermal loads.

10. Human entry into emplacement drifts shall be prohibited when waste packages are present.

11. Waste package materials for “high” thermal loading are (inner barrier) alloy 825 and (outer barrier) A516 carbon steel. Waste package materials for “low” thermal loading are (inner barrier) alloy 825, (middle barrier) A516 carbon steel, and (outer barrier) Monel 400.

12. No backfill (packing material) will be used in the emplacement drifts.

The Board understands that implementation of the “focused MGDS development” approach requires that assumptions be made. However, the assumptions should be consistent with current regulations,[27] necessary, and achievable. It is not immediately apparent that all of the above assumptions meet these tests. For example, the 4th key assumption above (criticality control for 10,000 years) seems inconsistent with current regulations, which do not appear to have a time limit for criticality control. The 5th assumption (waste package shielding) seems unnecessary; shielding thicknesses should be established based on straight-forward engineering tradeoff studies, not by assumption. Also, the 10th assumption (prohibiting human entry into emplacement drifts that contain waste packages) is an easy concept to imagine, but could be very difficult to accomplish where reliable and practical operations are required. The repository operations need to be worked out carefully to ensure that not only emplacement, but also long-term retrieval and monitoring can be successfully performed in the hostile underground repository area that must be served. The 10th assumption needs to be supported more thoroughly by operational analyses and the development of basic design concepts before it can be relied on given today’s state of the art in robotics, remote handling, and remote sensing.

Because important implied assumptions could have major impacts on the design, the Board is concerned about them as well. For example, the 9th assumption above could be taken to imply that performance confirmation monitoring may *not* be performed outside of special performance confirmation areas. Also, the different waste package material combinations (see the 11th assumption) imply that another assumption is being made about the periods of time during which liquid water could be in contact with waste packages for different thermal-loading strategies. Specifically, an implied assumption is being made that the “low” thermal-loading strategy will result in a longer period of contact between the waste packages and liquid water, and therefore that the waste packages will require an additional outer barrier (i.e., Monel 400, a nickel-copper alloy known to perform well in aggressive aqueous environments) to attain acceptable performance. This implied assumption depends on yet other assumptions about how the repository is designed and operated, such as the order in which spent fuel is received for emplacement at the repository, the amount of ageing of spent fuel that will take place before emplacement, and the extent and duration of repository ventilation. Implied assumptions should be identified and articulated, so that they may be evaluated and questioned.

27 *The Board recognizes that current regulations may change as a consequence of processes instigated by the* Energy Policy Act of 1992. *If the DOE feels confident about what some of the changes will be, it should identify them and ensure that design assumptions are consistent with them.*

The DOE is forging ahead rapidly in its implementation of the "focused MGDS development" approach. In taking this approach, the DOE must be very careful that all assumptions have been critically examined, are necessary, and are achievable. *All* assumptions must be clearly articulated and consistent with current regulations.

EBS Design Outside the Waste Package

The waste package is a very important component of the engineered barrier system. Any other engineered items in the repository outside the waste package that act to prevent, retard, or disperse the release of radionuclides to the accessible environment or that assist the waste package to perform its functions are important components of the engineered barrier system. Many ideas for EBS components outside the waste package have surfaced over the years. Examples include erecting metal or ceramic shields over the package to deflect any water seeping from drift roofs, bolting extra metallic mesh to drift walls to assist in dissipating waste package heat more uniformly, or placing quantities of various materials, such as iron or zeolites, that could alter or maintain the chemical and physical environment beneficially by reducing waste package corrosion rates, by reducing the solubility of radionuclides, or by sorbing radionuclides. Yet another example is the use of capillary barriers to prevent water from contacting the waste package. Capillary barriers were discussed during the Board's July 1994 meeting.

Although the Board is aware that the DOE intends to carry out a very limited study of "backfill" as part of performance assessment activities scheduled for this fiscal year, it sees no indications that the DOE's "focused MGDS approach" includes serious consideration of other ideas for EBS components outside the waste package. At first glance, many such ideas seem to be simple, inexpensive, passive, and robust and to offer the promise of improved repository performance. The Board believes it is worth investing some effort in identifying and evaluating potentially useful ideas *now*.

Performance Assessment and Corrosion Research

As will be discussed in the next section (risk and performance analysis), the DOE sponsored two complete total system performance assessments during 1993. (For convenience, these performance assessments will be referred to as TSPA-1993s.) The two TSPA-1993s were especially noteworthy in that they included, *essentially for the first time in DOE-sponsored TSPA efforts for Yucca Mountain*, rudimentary mechanistic models for the corrosion of the waste package container.

The TSPA-1993s illustrated the very important role that the waste package can play in repository safety over thousands of years or more. For example, in some TSPA-1993 simulations, assumptions were made that resulted in waste packages remaining dry and not failing for more than a million years. Under other assumptions, however, waste packages failed in less than 10,000 years. In these cases, carbon-14 was the single largest radionuclide released during the first 10,000 years and under certain circumstances exceeded the 1985 EPA standard of acceptability (as contained in 40 CFR 191, which currently is being reassessed). This relatively large release comes about, in part, because it is *assumed*, among other things, that once the waste packages have failed, carbon-14 (released when water reaches the cladding or as the spent fuel matrix dissolves) immediately transforms from solid to gaseous form (e.g., $^{14}CO_2$) and leaves the waste package.

These assumptions are felt to be overly conservative because they do not take into account the length of time required for oxygen to react with carbon-14 and the surface area of spent fuel matrix exposed to oxygen, the role that cladding could play as a barrier, or the possibility of adsorption of carbon-14 in gaseous form onto waste-package corrosion products. Furthermore, any failure of a robust waste package in less than 10,000 years most likely would be due to aqueous corrosion — which implies the presence of liquid water because aqueous corrosion to the point of failure requires prolonged contact between the packages and liquid water. Any liquid water present would be likely to absorb carbon-14 in gaseous form, thus preventing or retarding its journey to the accessible environment. (Carbon-14 could also be retarded in the far field by exchange with stable carbon isotopes in carbonates or tuff.) These and other assumptions will have to be reevaluated and, if necessary, replaced in future TSPAs by models that are not overly conservative and which, when integrated together, do not give such overly conservative and unrealistic results.

Although the use of rudimentary mechanistic corrosion models in the TSPA-1993s was a welcome step in the right direction, such models clearly must be refined, extended, and confirmed to become acceptable bases for predicting repository performance. An extensive suite of data to confirm modeling must be drawn from the literature *and gathered from a well-planned experimental program*. Such a program could require as much as a decade to complete and should be a prelude to an even longer-term repository performance confirmation program. An experimental program is already partially under way (at Lawrence Livermore National Laboratory, LLNL); however, these efforts are not yet underpinned by a formal long-range plan and do not appear to have the DOE's consistent support. Simply stated, failure to properly support such a program now will delay the entire repository program later because the long-term data needed to confirm performance models will not exist.

In March 1994, the EBS panel held a public meeting near LLNL to discuss current and planned research in the materials area. One of the speakers discussed at length the potential for microbially influenced corrosion at a repository in the Yucca Mountain unsaturated zone. Despite the fact that the stratum that would house the repository is unsaturated (i.e., the rock pores are partially, rather than completely, filled with water) and oxidizing (which implies that a very low level, if any, of organic nutrients is contained in the little water contained in the pores), ample evidence already indicates that small populations of microbes exist at the repository level. Subgroups of these microbes could flourish and multiply if nutrients are introduced to the repository — an almost inevitable consequence of exploring, constructing, and operating the repository. Any sound materials research program must address the question of microbially influenced corrosion at a repository at Yucca Mountain.

The TSPA-1993s also showed that waste package materials performance depends substantially on when the environment changes from dry to wet. It is necessary to be able to predict if and when liquid water (including high-humidity conditions) will be present at the repository level. Such predictions require exceptionally complex two-phase (liquid and gaseous) flow models as well as a great deal of confirmatory hydrologic data from the repository level. These data and the two-phase models will be needed to confirm the basis for the waste package design.

Defense Wastes

National policy calls for defense wastes (defense-related spent nuclear fuel and high-level wastes) and civilian waste (civilian spent fuel and high-level wastes) to be disposed of *together* in one or more deep geologic repositories. Should Yucca Mountain be found suitable and licensed, the DOE currently plans to dispose of the equivalent of approximately 7,000 metric tons of defense wastes there, along with 63,000 metric tons of predominately civilian spent fuel.[28]

Since defense wastes will account for only a small portion of the waste going to the proposed repository at Yucca Mountain and because defense wastes have a smaller amount of long-lived radionuclides than civilian spent fuel — per metric ton — the Board has devoted less attention to issues related to high-level defense wastes. The last time the EBS panel discussed defense wastes in writing was in the Board's *Sixth Report*, issued in December 1992, which followed its May 1992 public meeting in Richland, Washington, and a visit to the Hanford site. In June 1994, the EBS panel held a public meeting at Richland regarding repository-related defense waste issues at the DOE's Hanford Site; after the meeting, Board members and staff toured the site. The primary purpose of the meeting and tour was to learn of changes to the DOE's plans for dealing with Han-

28 "Metric tons" is short for metric tons of uranium or metric tons of heavy metal.

ford's high-level defense wastes since the panel's last visit. The Board also was interested in hearing about the process the DOE is using to develop plans for the disposal of Hanford spent fuel.

In terms of radioactivity, the high-level defense wastes at Hanford consist mostly of "tank waste" (high-level liquids and sludges from plutonium production stored in 177 large tanks) and strontium and cesium capsules (strontium-90 and cesium-137 recovered years ago from tank waste and sealed in small metallic capsules as fluoride and chloride salts, respectively). The spent fuel at Hanford is chiefly fuel that was irradiated in Hanford's plutonium production N-reactor but from which the plutonium was never separated. Board observations that resulted from the panel's visit are discussed below.

Hanford wastes

1. The planning basis for Hanford's high-level waste has changed significantly for the better since the last EBS panel visit. Since 1989, the DOE's plans and actions at Hanford have been performed under the Tri-Party Agreement, a written agreement among the DOE, the United States Environmental Protection Agency, and the Washington State Department of Ecology that governs the proper handling of mixed radioactive and hazardous wastes. The agreement was last amended in January 1994. Among the many changes in that 1994 amendment was the elimination of plans to mix low-level waste with cement and sand and dispose of the resulting grout on site in vaults; another change was a 10-year delay in constructing a plant to vitrify high-level tank wastes. The decision to delay plant construction has given Hanford some very important breathing room during which it can consider how to improve the waste form of the high-level waste that ultimately will go to a repository, as well as the process for making the waste form.

Hanford's current strategy is to retrieve waste from the tanks, primarily by sluicing, and use pretreatment processes (yet to be developed) to separate the retrieved waste into two waste streams: a liquid stream and a slurry stream. After additional treatment to make it a low-level waste, the liquid stream would be vitrified into glass logs for retrievable disposal on site at Hanford. The slurry stream would be vitrified into glass logs for disposal in a geologic repository. The January 1994 amendment to the Tri-Party Agreement allows Hanford time to investigate many pretreatment and vitrification variations of its current strategy.

A number of technologies will have to be developed, adapted, or perfected as part of the current strategy. For example, existing methods for retrieving tank wastes by sluicing may prove unsatisfactory for the tanks that are leaking; new retrieval technologies would have to be developed. In addition, the DOE may decide it is worthwhile to reduce the volume of high-level waste glass to lower disposal costs. If it does, new volume-reduction technologies will have to be developed. Finally, the capacity required of a high-level waste melter currently is beyond the state of the art; this means there is a need for an innovative program to increase the capacity of melters.

At the technical level, personnel at Hanford realize that the OCRWM has changed the repository baseline to include a large, drift-emplaced waste package for spent fuel (which could be a multipurpose canister). This change and the 10-year reprieve on vitrification plant construction will allow Hanford the time and option to investigate waste packages larger than the "standard" 2ft-diameter x 12ft-long waste package that the DOE's Savannah River facility will use.

Other potential changes being investigated at Hanford include making glass in a granular form, such as glass cullet or "marbles," rather than using a monolithic glass log; using nonborosilicate glasses, for example, aluminosilicate glasses; and developing glass melters that would operate at higher temperatures than borosilicate glass melters.

2. Hanford's strontium and cesium capsules raise interesting disposal questions. In the early 1970s, a campaign was launched to remove the bulk of the strontium-90 and cesium-137, which generate high amounts of heat, from waste tanks to avoid "hot-spots" in the tanks. The strontium-90 and cesium-137 removed from the tanks were converted to strontium fluoride and cesium chloride and encapsulated into nearly 2,000 double-walled metal capsules 6.6cm in diameter x 52.1cm long. The strontium and cesium capsules are high-level radioactive waste and require disposal in a repository. They are an important waste because their total radioactivity and heat generation rate almost equal the total radioactivity and heat generation rate of the tank wastes.

Hanford wants to resolve the issue of whether the repository will be able to accommodate the strontium fluoride and cesium chloride capsules in some sort of overpack arrangement and, if so, to determine what sort of arrangements for disposal would be acceptable. If overpacking is not acceptable, would blending the strontium fluoride and / or cesium chloride into selected tank waste streams for vitrification be acceptable? Hanford needs an answer relatively soon regarding whether the strontium fluoride and / or cesium chloride encapsulated waste will require vitrification because of the very long lead time required to design and build facilities to remove the waste from the capsules, perhaps chemically convert it, and then blend it into a vitrification stream. The Board believes that the DOE should initiate studies immediately to determine what forms would be acceptable for repository disposal for encapsulated strontium and cesium.[29]

3. A large amount of spent fuel is stored at Hanford that will require disposal in a repository. A significant amount of the spent fuel produced at Hanford was never reprocessed. Almost all of it currently is stored under water in the K-East and K-West basins, located in the northern part of the Hanford site. There are 2,100 metric tons of spent fuel in the two basins; essentially all from the N-reactor. The K-East basin is heavily contaminated with corrosion-product sludges, while the K-West basin, which contains approximately the same amount of spent fuel, is comparatively clean. Because the K-basins are within 200 meters of the Columbia River and particularly because the K-East basin has leaked and is likely to leak again, very high priority is being placed on removing the spent fuel and sludges as soon as possible, putting them in a safe form somewhere on site but away from the river, and draining and cleaning the basins. Personnel at Hanford are developing plans for putting K-basin spent fuel into a safe storage status. Unfortunately, however, it does not appear that planners are considering the fact that the spent fuel ultimately will be disposed of in a deep geologic repository.

The Board believes that the DOE should ensure that its Office of Environmental Management is aware of general repository requirements for spent fuel. The Board also believes that the DOE should develop specific repository requirements applicable to DOE-owned spent fuel. More generally, the Board believes that, whenever possible, the DOE must develop internal coordination to ensure that repository requirements are considered when planning any major action involving DOE-owned spent fuel.

4. Interactions between the Office of Environmental Management (EM) and the OCRWM have improved but important gaps remain. Two years ago, communication between the EM and the OCRWM regarding Hanford wastes that would be disposed of in a repository was minimal. However, formal and informal interactions between them regarding Hanford wastes have increased significantly since then.

Yet two serious gaps remain: (1) To be able to determine the optimal ranges of waste package size, glass form and composition, degree of treatment of tank waste before vitrification, and other parameters, EM must have a reasonable idea of how varying these parameters could affect repository performance. Unfortunately, the OCRWM's total system performance assessment calculations to date, although including glass waste forms to a limited extent, have not been sufficiently detailed to provide useful guidance to EM; (2) At EM's request, the OCRWM performed estimates of how disposal of different numbers of canisters of vitrified waste would affect total disposal costs. These estimates were based on a 1990 version of total system life cycle cost estimates, which are now badly out-of-date because of changes by the OCRWM in the waste management system baseline. A new total system life cycle cost estimate has been promised for the end of fiscal year 1995; should be very useful as EM makes decisions about

29 An agreement and a mechanism exist within the DOE for the internal transfer of funds from the Office of Environmental Management (the DOE office responsible for Hanford) to OCRWM to cover such studies.

high-level waste processing and packaging. Although the Board commends the OCRWM and EM for their improved interactions, it believes that the OCRWM's performance assessments should address glass waste forms and other defense waste forms at a sufficient level of detail to be useful to EM in discriminating among various waste forms and waste package sizes. Because a new total system life cycle cost estimate is needed not only for guidance for EM but also for the civilian spent fuel disposal program, the Board urges the OCRWM to complete the revised total system life cycle cost estimates without delay.

5. Comparing the amounts of commercial spent fuel and defense wastes presents an "apples and oranges" dilemma. Since 1944, Hanford has produced more than 100,000 metric tons of spent fuel from its production reactors. This is considerably more than the entire current U.S. civilian reactor population will produce under many plausible scenarios. However, primarily because of the very low burnup of defense spent fuel, Hanford personnel claim that the tank waste (derived from reprocessing spent fuel) is equivalent to only about 2,600 metric tons of commercial spent fuel. The Nuclear Waste Policy Act currently requires the NRC to "prohibit the emplacement in the first repository of a quantity of spent fuel containing in excess of 70,000 metric tons of heavy metal or a quantity of solidified high-level radioactive waste resulting from the reprocessing of such a quantity of spent fuel until such time as a second repository is in operation...."(NWPA 1982, Sec. 114); the act does not speak to adjustments for burnup. In other words, at least for the purposes of this clause, the Nuclear Waste Policy Act seems to imply that the amount of high-level tank waste at Hanford would be considered equal to 100,000 metric tons of heavy metal and not the 2,600 metric tons (adjusted for burnup) as claimed by Hanford personnel. This is an important technicality that, if confirmed, may be remedied easily in legislation.

Surplus weapons fissile materials

The DOE is developing plans for disposition of surplus weapons fissile materials. "Weapons fissile materials" include weapons-grade plutonium (plutonium containing approximately 90% plutonium-239), highly enriched uranium (uranium containing more than 20% uranium-235), and comparatively minor amounts of other fissile materials, such as uranium-233, neptunium-237, and americium-241. The defense fissile material with the greatest potential implications for geologic repositories is the weapons-grade plutonium. Approximately 50 metric tons of U.S. weapons plutonium are likely to become surplus to the nation's needs due to the changing international situation. The Secretary of Energy created a project to plan for the control, storage, and disposition of surplus nuclear materials; the Under Secretary of Energy has the oversight of this project. The project has initiated a programmatic environmental impact statement (PEIS) to evaluate various options for the long-term storage of all weapons-usable fissile materials and disposition of weapons-usable fissile materials declared surplus to national defense needs by the President.[30] The draft and final PEISs are to be issued in the summer of 1995 and the spring of 1996, respectively. Near-term disposition alternatives for surplus plutonium to be considered in the PEIS include the mixed-oxide fuel alternative (essentially substituting plutonium-239 for uranium-235 in existing, modified, or new light water reactors), the vitrification alternative (essentially vitrifying weapons plutonium with high-level waste at Savannah River or Hanford), and the deep borehole alternative (disposing the weapons plutonium, with or without chemical modifications, in very deep holes). Longer term dispositions to be examined in the PEIS include the accelerator-based conversion alternative (destruction of plutonium by fission in a subcritical reactor by neutrons produced by an accelerator) and the "deep-burn" reactor alternative (reactors in which plutonium could be fissioned virtually to extinction).

It is recognized that many of the above alternatives could affect at least part of the material coming to

30 The notice of intent to prepare the PEIS was published in the Federal Register *(59 FR 31985-90, June 21, 1994).*

repositories. Studies are already under way in the OCRWM to determine if these effects could be significant.

Conclusions

1. The DOE is forging ahead rapidly in its implementation of the "focused MGDS development" approach.

2. Mechanistic corrosion models were used for the first time in TSPA-1993s, which confirmed the very important safety role that the waste package can play over thousands of years or more.

3. Planning for Hanford's high-level waste has changed significantly for the better since the last visit by the Board's panel.

4. Large amounts of DOE-owned spent fuel now being stored at Hanford will require disposal in a repository.

5. Interactions between DOE's Office of Environmental Management and the OCRWM have improved, but important gaps remain.

6. It is becoming increasingly clear that comparing the amounts of civilian spent fuel and defense wastes is an "apples and oranges" dilemma.

7. The DOE is developing plans for disposition of surplus weapons fissile materials; these materials could have implications for a repository.

Recommendations

1. In performing its "focused MGDS development" approach, the DOE must ensure that *all* assumptions about the repository system are clearly articulated, necessary, achievable, and consistent with current regulations.

2. To support waste package performance predictions, the DOE must develop a formal long-term corrosion research program plan and must support the program at an appropriate and consistent level. Failure to do so risks delaying the repository opening.

3. The Board believes that the DOE should address the issue of general repository requirements for both civilian and defense spent fuel; specific repository requirements applicable to DOE-owned spent fuel should be developed.

4. The Board recommends that the DOE immediately initiate studies to determine what waste forms for Hanford's encapsulated strontium and cesium salts will be acceptable for repository disposal.

5. The Board recommends that DOE's performance assessments address glass waste forms and other defense waste forms at a sufficient level of detail to assist the Office of Environmental Management as it makes decisions about waste forms and waste packages. The Board also recommends that the DOE not delay the completion of its revised total system life cycle cost estimate.

Risk and Performance Analysis

Total system performance assessment (TSPA) is the principal method for evaluating the ability of the proposed repository system (both engineered and natural components) to contain and isolate radioactive waste safely. It serves several functions. It will play an important part in the DOE's assessment of the suitability of Yucca Mountain to serve as the site of a high-level waste repository and, eventually, if the site is found suitable, it will be the primary measure by which the NRC will judge whether the proposed repository can be built and operated safely. At this stage, however, where site suitability and regulatory compliance are not yet being evaluated, TSPA can, and should, play a significant role in guiding site-characterization activities, assessing priorities, evaluating different engineering designs, and estimating the effects of contemplated changes in standards and regulations.

In this report, the Board describes the DOE's recent TSPA efforts. Some interesting technical insights are discussed that could provide useful guidance to the repository program. The DOE is both praised and criticized in the way it is making use of performance assessment. Several consistent messages about the Yucca Mountain site that are developing from past and present performance assessments are highlighted, and the need for the DOE to articulate a clear and coherent waste isolation strategy with respect to the disposal of high-level radioactive waste at Yucca Mountain is stressed.

Background

In 1994, several TSPAs evaluating the proposed repository at Yucca Mountain were published. These include two major DOE-sponsored studies, one by Sandia National Laboratories (SNL 1994) and one by Intera Corporation (Intera 1994). The SNL study is the second iteration of a 1991 TSPA that, along with a 1991 Pacific Northwest Laboratory TSPA, were discussed in the Board's *Sixth Report*. DOE also sponsored a TSPA-based set of calculations (Duguid et al. 1994) submitted to a special committee established by the National Academy of Sciences, whose purpose is to evaluate the technical basis for changes in the EPA standard for the proposed Yucca Mountain repository. The Electric Power Research Institute also submitted a set of TSPA calculations to the NAS committee for the same purpose. Finally, the NRC published a full-scale TSPA (NRC 1994) in the latter part of the year.

On January 12, 1994, the Board met in Arlington, Virginia, to hear presentations on draft versions of the three DOE-sponsored studies and the EPRI study; the NRC was not then in a position to discuss its results. Following are some technical insights developed at the meeting and in the subsequent reading of additional material that the Board believes need to be discussed. Included are some Board comments on the importance of these insights and on the need for further substantiation.

Technical Insights and Comments

1. *TSPA has made important steps forward since the last iteration in 1991.* In comparison to previous studies, the SNL and Intera TSPAs have increased the hydrological, geochemical, and geologic database on which the analyses are founded; they have expanded models for waste-package corrosion and performance;[31] they have incorporated near-field thermohydrologic behavior into the analyses; and they have expanded the treatment of external factors such as climate change, volcanism, and human intrusion. The two main studies (SNL 1994 and Intera 1994) approached the calculations somewhat differently. SNL relied more on direct model calculations and data analysis, allowing for the incorporation of many important details. The Intera study was more abstracted, that is, removed from direct calculations of the processes, relying more on functional relationships determined by outside modeling studies, but with an enhanced capacity to represent input parameters, and their correlations, statistically.

Repository thermal loading, and the mode of radioactive waste emplacement were addressed specifically to determine the effect of different repository design assumptions on performance. As an adjunct to these calculations, the sensitivity of the results to thicknesses of waste containers was also addressed. The SNL and Intera studies looked at the manner in which different assumptions affected the different performance measures, that is: the complementary cumulative distribution function, which displays the probability of exceeding different levels of radionuclide releases to the accessible environment;[32] and individual dose, the dose of harmful radiation received by maximally exposed individuals due to the presence of a repository. They also examined changes in performance over periods ranging from 10,000 years (found in 40 CFR 191) to 100,000 and one million years. The Duguid et al. (1994) and EPRI (1994) studies concentrated on the sensitivity of the calculated results to different performance measures and periods of performance. As indicated above,

31 *For a more complete description and evaluation of these models, see the section in this chapter on the engineered barrier system.*

32 *These release levels have typically been normalized to fractions and multiples of the 1985 EPA standard (40 CFR 191), the original measure of repository performance that is currently being reassessed.*

these studies were conducted in support of the NAS committee which was charged with examining the technical bases of a Yucca Mountain standard.

2. *Gaseous carbon 14 is calculated as being the single largest radionuclide release for at least 10,000 years*. The Board's *Sixth Report* (NWTRB 1992b) noted that TSPA in 1991 showed gaseous carbon-14 to be the single largest radionuclide release from the repository during the first 10,000 years. Indeed, under certain assumptions, this release exceeds the 1985 EPA standard of acceptability. This is still true in the latest round of TSPA calculations. The relatively large release comes about because once the waste container corrodes, it is assumed that the gas will rise quickly to the surface through interconnecting fractures.[33]

This phenomenon is limited to repositories in the unsaturated zone. Below the water table carbon-14 dissolves in ground water and travels much more slowly along with other radionuclides. Gaseous releases could be contained by very robust (and, perhaps, very expensive) waste containers. The dilemma facing those constructing a repository is that as large as these releases may seem, they only constitute a very small percentage of carbon-14 already present in the atmosphere due to natural and industrial releases. The NAS committee on the technical basis for the Yucca Mountain standard is addressing the significance of gaseous releases from a proposed repository.

3. *Percolation flux and conceptual models of flow and transport in the unsaturated zone are the most important scientific issues affecting performance*. The amount of liquid water that is assumed to reach the proposed repository, corrode waste containers and (in the case of aqueous releases) entrain harmful radionuclides and the ability and speed by which ground water can transport these radionuclides are the key scientific issues affecting the ability of the natural and engineered barriers to contain and isolate radioactive waste. Factors that can affect flow and transport include: future climate, particularly the magnitude and timing of precipitation and attendant evapotranspiration; the presence of fractures that can act as fast paths for ground-water flow; and the extent to which the volcanic tuff underlying the repository horizon can slow the movement of radionuclides within the ground water by sorption.

Although data have been collected since 1991, only the additional information available from underground exploration and testing and drilling will allow progress in reducing the uncertainties associated with flow in the unsaturated zone. It should be noted (and this will be pointed out later) that, in the present arid climate and barring the existence of numerous, as of yet undiscovered, fast paths, aqueous releases are calculated to be very small and well below the release limits for 10,000 years specified in the 1985 EPA standard.

4. *Current TSPA calculations show different thermal-loading strategies having relatively little effect on performance*. Of particular interest were the sensitivity tests conducted with respect to assumptions regarding thermal loading of the repository. Three thermal-loading strategies were evaluated in the current round of TSPAs: the 57kW/acre strategy, outlined in the 1988 *Site Characterization Plan*, which predicts that a large portion of the rock in the immediate vicinity of the repository will remain above the boiling temperature of water for approximately 300 to 1,000 years; 114kW/acre, which results in above-boiling temperatures being maintained in the nearby rock for up to 5,000 to 10,000 years; and 28.5kW/acre, at which the nearby rock average temperature is presumed to remain below boiling. According to the current TSPA calculations, there is only a slight advantage in the lower (28.5kW/acre) and higher (114kW/acre) thermal-loading strategies over the SCP strategy. Differences that do exist primarily depend on the assumed time the surface of the waste container is in the temperature range of aggressive corrosion (temperatures above 60°C and relative humidity above approximately 70%).

The Board would like to emphasize that it is too early to draw firm conclusions from these model

33 The rapid transport of gaseous carbon-14 to the surface is based on several assumptions. For a discussion of these assumptions and their conservatism see the section in this chapter on the engineered barrier system.

results, given the assumptions used in the TSPA models. Much is not known about the long-term thermo-hydrological behavior of the rock-water system in the unsaturated zone, and relatively little work has been done on simulating the "low" thermal-loading scenarios, and those that result in above-boiling temperatures for periods in excess of 10,000 years. The DOE needs to address these issues. If, indeed, further tests and analyses support the present calculations, repository performance cannot serve as a useful discriminator in selecting the appropriate thermal-loading strategy.

5. *Current TSPA calculations show mode of emplacement having little effect on repository performance.* Both the emplacement of the waste containers in small-diameter vertical boreholes and the direct horizontal emplacement of containers in larger diameter drifts were examined. The only differences were noted when human intrusion (through vertical drilling from the surface) or throughgoing vertical fractures were assumed to exist. In those cases, horizontal emplacement of the containers in drifts yielded larger cross sections affording a better target for vertically directed flow or disruptions. Even in these cases the differences were small.

It should be noted that the disruptive effects of earthquakes were not assessed in the SNL and Intera TSPAs. As indicated in the *Fifth Report* (NWTRB 1992a), the larger freeboard (distance between the waste package and the surrounding rock) in horizontal drift emplacement would greatly reduce the impact of direct faulting on the integrity of waste packages. The primary advantage of horizontal emplacement is the greater ease with which large, robust waste packages or multipurpose canisters can be handled underground.

6. *Current TSPA calculations show that thick waste packages can reduce releases for 100,000 years.* Three thicknesses of steel for the outer waste container were assumed, 10, 20, and 45 cm. Although 10- and 20-cm thick packages showed little relative difference in the calculated 10,000 and 100,000 year cumulative releases,[34] the assumption of a very thick, 45-cm outer package yielded virtually no releases in the first 10,000 years, and substantially less release than the other waste package configuration during 100,000 years. At 1,000,000 years there was no difference in performance from the different thicknesses of waste packages.[35] These calculations indicate that increasing the thickness of the steel waste container has little effect on performance until substantially thick steel is used. At extremely long periods (1,000,000 years), the packages have been compromised by corrosion regardless of their thickness.

Even if substantiated, these calculations would not automatically suggest that the waste be disposed of in very thick outer containers. The DOE would have to examine the tradeoffs between increased containment of the waste, the reduced significance of uncertainties in the natural barriers (such as retardation), ease of handling, public perceptions, and overall program costs. Increasing protection of the public and the environment is of course paramount, but other considerations have to be taken into account.

7. *Flow and transport in the saturated zone become particularly important in calculating individual dose.* When calculating the amount of radionuclides released from the proposed Yucca Mountain repository that reach the accessible environment, little credit is usually given to the saturated zone acting as a barrier to the transport of harmful radionuclides. Typically, the time required for these radionuclides to move in the saturated zone is short compared to that in the unsaturated zone between the repository and the water table. When calculating individual dose, however, another factor becomes critical, that is, how concentrated the release is at a particular time and place.[36]

34 *Based on the Intera (1994) study, there is some indication that the combination of a "low" thermal-loading strategy (28.5kW/acre) and a 20 cm thick outer waste container would delay failure of the waste package for more than 10,000 years.*

35 *In contrast to 10,000 and 100,000 years, where the primary calculated measure of performance in the SNL (1994) and Intera (1994) studies is cumulative release, individual dose is the primary performance measure at 1,000,000 years.*

36 *Saturated zone transport may actually not be as rapid as is usually assumed and can also contribute substantially to safety even when measuring performance by cumulative releases over 10,000 years. This was one of the more interesting results of the* Calico Hills Risk Benefit Analysis *(DOE 1991) carried out by DOE contractors in 1989-1990 and discussed in the* Third Report *(NWTRB 1991a).*

Calculated individual doses can be quite large, particularly at periods much longer than 10,000 years, when more radionuclides are assumed to reach the saturated zone.

At arid sites, such as Yucca Mountain, little water is available to dilute the radionuclides that eventually do get released. Dilution by large amounts of water in the saturated zone could minimize radionuclide concentration and, therefore, the dose. It is no surprise that if it is assumed that there is mixing of ground water to great depths in the saturated zone, the dilution will be greater and the dose smaller. All the current TSPA calculations support the case that if individual dose becomes an important performance measure (under consideration by the NAS committee on the EPA standard), an increased knowledge of the saturated zone will be required. Additional factors that become important include the solubility of neptunium-237 (the dominant contributor to individual dose at very long periods) and modeling the biosphere, which is not needed when calculating releases.

Making Good Use of Performance Assessment

The DOE appears to be making effective use of simple performance assessments (not full-blown TSPAs, sometimes merely back-of-the-envelope calculations) to evaluate the impact of different site-characterization and construction activities on waste isolation.[37] Examples of such activities include: the use of a diesel underground transportation system; hydrocarbon spill remediation in drill holes; and the use of tracers, fluids, and other materials in tests. The Board is pleased that performance assessment, albeit relatively simple, is meeting some of the program's practical needs.

However, the DOE has not demonstrated systematic and effective use of total system performance assessment. At this stage, TSPA should be used in providing programmatic guidance to site characterization, particularly in defining critical assumptions and setting scientific priorities. Typically, TSPAs in 1991 and 1993 have summarized their conclusions with generalized discussions of the important lessons learned and their significance to activities such as site characterization and design. The Board has not yet seen evidence that these conclusions are presented systematically or have had a strong effect on the program.

A useful example of the systematic presentation and use of performance assessment can be found in studies conducted for the WIPP. After completion of a performance assessment for the WIPP, the various input parameters are listed and ranked according to their importance and assessments are made as to the value of gaining additional information on different elements of the engineered and natural system and of increasing the level of understanding of the different conceptual models. The adequacy of the computer codes also is evaluated. Finally, completeness with respect to eventual demonstration of compliance is assessed. Those people responsible for testing use this information to set priorities. At different times in the past, performance assessment has led to emphasis on studying the inflow of brine (the WIPP is in an underground salt formation), engineering alternatives, and gas generation. Performance assessment helped point out the significance of human intrusion at the WIPP site.

The Yucca Mountain program could learn from, and even improve upon, the use of performance assessment at the WIPP. Systematic evaluation and ranking of scientific testing and engineering alternatives, identification of what new information is important and *what is not important*, would, *if used*, not only help focus attention and resources on activities that really count, but it would also help the DOE demonstrate progress. Management and organizational commitments are needed here.

37 This paragraph is based on material presented by Jean Younker (TRW) at the January 1994 Board meeting.

A Consistent Message about the Yucca Mountain Site from Current and Past Performance Assessments

An intriguing summary of current and past performance assessments was presented at the Board's January 1994 meeting.[38] The presenter pointed out that these assessments, conducted since 1982, consistently backed the following three conclusions: (1) A Yucca Mountain repository, under nominal (that is, normal and likely future) conditions, will release small amounts of harmful radionuclides into the ground-water system for an assumed performance period of 10,000 years. These releases are well below existing criteria. (2) A Yucca Mountain repository will release greater amounts of gaseous radionuclides (carbon-14) into the atmosphere under nominal conditions and greater amounts of harmful radionuclides into the ground water under unlikely conditions (such as very high percolation flux and low retardation). These releases could exceed some existing criteria. (3) A Yucca Mountain repository, under nominal conditions, will result in large individual doses at periods longer than 100,000 years. These doses could be well above existing criteria.

The Board believes it is important to note that many of the calculations underlying these assessments are based on simplified models and inadequate knowledge, not reflecting, for example, the complexities and details of unsaturated flow at Yucca Mountain, the amount and rate of carbon-14 actually released from a waste package, or the extent to which ground water near a repository would be used for drinking. Undoubtedly, the results of performance assessment will change as greater model complexity is achieved and more information is gathered. However, as discussed in the Board's analysis of the latest round of performance assessments, the general thrust of the three conclusions cited above stems from the very nature of Yucca Mountain's location in an arid region underlain by a very deep water table. Future performance assessments probably will still show that Yucca Mountain site is a "good" site with respect to likely aqueous releases over the next 10,000 years, that it may be a "problematic" site with respect to likely gaseous releases and unlikely aqueous releases, and that it may "not be a particularly good" site if individual doses over periods longer than 100,000 years are emphasized.

An NAS committee is assessing the technical basis for, and eventually the EPA will be revising, the basic standard for determining the acceptability of the Yucca Mountain site. The revised standard and the NRC regulations that are derived from it, will have to address the significance of gaseous and aqueous releases, individual dose, and period of performance to public health and the environment.

For its part, the DOE will have to weigh how the Yucca Mountain site, whose salient characteristics are not likely to change, will fare against the new standard and regulations. If the new criteria are potentially in conflict with the site's characteristics (for example, if gaseous release during the first 10,000 years or individual dose over hundreds of thousands of years are considered most significant), it may be possible to use engineering to mitigate some adverse effects. If this is not possible or if deemed inappropriate, the DOE may have to determine whether further expenditures on the Yucca Mountain, or any other similar unsaturated zone site are worthwhile.

Whether a viable synthesis of the natural and engineered aspects of a proposed repository can be made depends on the DOE's success in articulating a clear and coherent waste isolation strategy, as described below.

Performance Assessment and a Waste Isolation Strategy for Yucca Mountain

At its January 1994 meeting, the Board heard several presentations that emphasized the importance of defining a *safety concept*, or waste isolation strategy, in siting and designing a high-level radioactive waste repository.[39] A waste isolation strategy has been used successfully

38 *"Evolution and Performance Assessment in the Yucca Mountain Project" by Scott Sinnock (TRW).*

39 *Report by Tom Isaacs (DOE) on the activities of the Alternative Program Strategy Task Force and a report from Sweden by Nils*

by other countries (most notably, Sweden) to articulate clearly and concisely how a proposed repository will safely contain and isolate harmful radionuclides from the public and environment under a range of future conditions. An essential part of such a strategy is the assigned roles the different natural and engineered barriers play in waste isolation and their relative importance. Such a strategy can serve as a focused basis for planning and setting priorities in site characterization and designing the repository.

The DOE attempted to outline elements of a waste isolation strategy for Yucca Mountain under the subject of *top-level strategy* in the introduction to Chapter 8 of the 1988 *Site Characterization Plan* (DOE 1988). Performance goals for the individual barriers and site investigation priorities were then defined following a very complex process of *issue resolution* and *performance allocation*. The waste isolation strategy for Yucca Mountain needs to reflect new information, and most important, needs to be presented in a manner that is both understandable and useful to those working on, or interested in, Yucca Mountain.[40]

Performance assessment is an analytical method by which the strategy can be refined and tested with respect to its success in isolating waste. Performance assessment, however, is no substitute for a waste isolation strategy. As in other projects, risk analysis (of which performance assessment is a subset) can not take the place of design. The Board believes that the articulation of a clear and coherent waste isolation strategy for the proposed Yucca Mountain repository would serve a very useful purpose and urges the DOE to develop one.

Conclusions

The DOE is making progress in many aspects of its performance assessment program for Yucca Mountain. It has successfully completed its second iteration of TSPA and is preparing for the next iteration, tentatively planned for 1995. Although simplified performance assessments have been used successfully in assessing the impact of site-characterization and construction activities, the DOE has yet to demonstrate that it is making systematic and effective use of TSPA in guiding site characterization and setting priorities.

Current calculations (which need to be substantiated) show little effect on performance by assuming different thermal loadings or modes of waste emplacement and some effect by assuming different thicknesses of waste containers. Gaseous carbon-14 appears to be the largest radionuclide that would be released over the first 10,000 years or more, while the conceptual models of flow of water and transport of radionuclides in the unsaturated zone are the most important scientific issues affecting performance. When considering individual dose, particularly at long periods, saturated zone flow and radionuclide transport, in particular dilution, become very important.

Performance assessment over the years has given generally consistent results that reflect both the advantages and disadvantages of siting a repository in an arid area underlain by a deep water table. The DOE needs to take such characteristics into account along with postulated changes in the EPA standard and the NRC regulations and articulate a clear, coherent, and detailed waste isolation strategy. Such a strategy defines the roles of natural and engineered barriers in protecting the public and the environment from the long-term presence of a high-level radioactive waste repository. If there is a fundamental conflict between the basic characteristics of the Yucca Mountain site and the new standard and regulations such that a clear and coherent waste isolation strategy is not feasible, the DOE will need to reassess whether further expenditures on the Yucca Mountain, or any other unsaturated zone, site are worthwhile.

Rydell (Swedish National Council for Radioactive Waste).

40 *The importance of articulating a clear waste isolation strategy was brought out in the presentation by NWTRB Chairman John Cantlon and NWTRB member Garry Brewer to the U.S. Nuclear Regulatory Commission on September 9, 1994. At the October 12, 1994, and January 11, 1995, Board meetings, the DOE presented an outline of a proposed new waste isolation strategy.*

Recommendations

1. The DOE needs to articulate a clear and coherent waste isolation strategy that takes into account the salient characteristics of the Yucca Mountain site, the ability and desirability of engineered barriers to enhance waste isolation, and postulated changes in the basic standard and regulations that will be used to assess the performance of the proposed repository.

2. In light of the successful completion of the 1993 round of TSPAs, the Board encourages the DOE to continue its program of iterative performance assessment.

3. The DOE needs to make a management and organizational commitment to develop more systematic and effective ways of using total system performance assessment to guide site characterization and to set priorities at Yucca Mountain. The Board suggests that the DOE learn from the manner in which performance assessment was and is being used for the WIPP in New Mexico.

Chapter 5
Observations from the Board's Trip to Japan

In May 1994, the Nuclear Waste Technical Review Board continued its interest in the nuclear waste disposal programs of other countries by sending a small delegation to visit Japan to be briefed on that country's program for managing spent fuel and disposing of high-level radioactive waste. The week-long, intensive schedule included meetings with representatives of the Atomic Energy Commission, Japan Nuclear Fuel Limited (JNFL), the Power Reactor and Nuclear Fuel Development Corporation (PNC), the Science and Technology Agency, and the Steering Committee on High-Level Radioactive Waste Project. In addition to meeting with headquarters personnel from some of these organizations, the Board delegation also had the opportunity to tour the facilities under construction at JNFL's Rokkasho-mura site and to visit the PNC's research and development facilities at the Tokai Works, Chubu Works (now called the Tono Geoscience Center), and Kamaishi.

The members of the delegation were very appreciative of all of the experts who took time to meet with them. Board members would especially like to thank all of those involved from PNC who coordinated and arranged the myriad of transportation, meeting, and administrative details that made this visit possible.

Differences and Similarities

The various countries' programs visited by the Board to date have differed in a number of important ways from the U.S. nuclear waste disposal program, and Japan's program is certainly no exception. Despite the differences, however, the Board believes that both the U.S. and Japanese programs may benefit from continuing exchanges on certain aspects of their respective approaches. This report briefly describes the scientific and technical differences and discusses some of the underlying bases for these differences as reflected in the overall approach each country has taken toward meeting the challenge of its nuclear waste disposal.[1]

Saturated Versus Unsaturated Zone

As with other countries working on nuclear waste disposal, both the United States and Japan have concluded that deep underground geologic disposal is the best option. In Japan, any deep geologic repository would be located in the saturated zone in crystalline or sedimentary rock. Therefore, a potential repository must be designed in such a way as to withstand substantial water infiltration. Most of the generic research on repository development worldwide has been performed above or below ground in the saturated zone. As a result, these countries have the advantage of being able to learn from each other before selecting a site for a permanent repository.

In contrast, the potential site of the U.S. repository is located at Yucca Mountain, Nevada, in tuffaceous rock (tuff) in an unsaturated zone that is more than 500 meters thick. The proposed repository would be approximately 300 meters below the surface but 200 to 300 meters *above* the water table. Consequently,

1 *Appendix I of this report provides an overview of Japan's nuclear waste management system.*

although the U.S. program is studying potentially very favorable geologic and hydrologic conditions at Yucca Mountain, less is known about the unsaturated zone relative to the body of research worldwide on the saturated zone.

In addition, the emphasis in the past in the U.S. program has been to place primary reliance on the natural barriers for isolation of radionuclides. Thus, more emphasis has been placed on characterizing the geology than on research in the area of engineered barriers. Because less is known about the unsaturated zone, and little, if any, research has been performed that could help in choosing compatible engineered barriers, the U.S. strategy may be more difficult to evaluate from a scientific and technical perspective.

Assessment of Volcanic, Seismic Hazards

One of the major reasons the Board took the trip to Japan was to learn more about the work there in the area of volcanic and seismic hazards and to see if that work could benefit the site-characterization efforts at Yucca Mountain. Major volcanic eruptions have not occurred in southern Nevada for more than 6 million years. One focus of concern is the potential for renewed volcanic eruptions or intrusions of a lesser magnitude in the immediate area of Yucca Mountain.[2]

Japan sits on the western edge of the Pacific Ocean's so-called "Ring of Fire," a region that is among the most tectonically active in the world. Japan has approximately 200 active volcanoes, yet less than 1 percent of the earth's surface; three of the earth's shifting tectonic plates intersect there. As a result, work aimed at studying the potential effects of earthquakes and volcanoes on the geology and hydrology is important. PNC is conducting a series of experiments at its Kamaishi facility (an abandoned iron mine) to verify the previously observed reductions (in this case by 50%) in earthquake ground motion at depth compared to the surface. Another experiment there has measured changes in the ground-water hydrology and geochemistry immediately after an earthquake. The purpose of this work is to study the long-term physio-chemical stability of the geologic environment. It would be useful for the U.S. program to keep abreast of this work, to determine if it provides any insights into possible earthquake-induced changes in the hydrologic regime of the proposed Yucca Mountain site.

Engineered Barrier System Approach

In Japan, the current approach is to rely on the engineered barrier system to isolate the waste and build confidence in the reliability and safety of a repository for high-level waste.[3] This approach is necessary in part because the "characterization of a geologic setting may be difficult due to geologic heterogeneities. The variability of natural conditions causes large uncertainties in the predicted performance of natural barriers (Yamato et al., 1992)." The engineered barrier relies on three main defenses: (1) a vitrified waste form, which is virtually insoluble; (2) a thick steel overpack, which provides both physical isolation of the glass and chemical buffering of the pore water in the backfill; and (3) a massive bentonite backfill, which controls both flux and chemistry of the ground water reaching the overpack and the vitrified waste form. (Yamato et al., 1992).

Although decades away from designating a specific disposal site, PNC is in the process of conducting full-scale experiments to test the performance of potential waste containers. In addition to studying ground-water flow and geochemistry (see below), PNC is studying the adequacy and performance of potential engineered barrier materials. The corporation also is experimenting to determine the total performance of the multibarrier system. For example, at

2 *See Chapter 3 of this report, "Resolving Difficult Issues — Volcanism."*

3 *In the case of Japan, the term "engineered barrier system" refers to the radioactive waste material (high-level waste from reprocessing spent fuel) and any encapsulating or stabilizing matrix, any containers or shielding surrounding them, any packing or absorbent material immediately surrounding the containers or shielding, any underground openings in which the waste is emplaced, and any backfill materials used in the openings.*

the Big Ben facility at Tokai Works, PNC is conducting a *full-scale* simulation of coupled thermal-hydrological-mechanical (THM) processes surrounding an emplaced container. Tests to study the lifetime and integrity of engineered barriers, the mechanical behavior of buffer material, and the coupled thermo-hydro-mechanical processes in the near field also are underway at the Geologic Isolation Basic Research Facility at Tokai Works.

In the U.S. program, the engineered barrier system's nature and role in isolating the radionuclides are still evolving. For many years, the baseline U.S. engineered barrier system was the one described in the 1988 Site Characterization Plan. It consisted of a low-capacity, thin-walled, steel waste package that would be emplaced in vertical boreholes excavated in the floor of emplacement drifts. The drifts would remain open to allow easy retrievability for a performance confirmation period on the order of 50 years, at the end of which time the drifts would be backfilled with mined-out material and permanently closed and sealed. Since the thin-walled, waste package was expected to provide containment for only 300 to 1,000 years, primary reliance was to be placed on the natural geology to isolate the radionuclides over the long term.

During the last few years, however, the DOE has been considering larger, thicker walled waste packages[4] and reexamining the universal cask concept. The Board has recommended the universal cask because of its potential for standardization and improved safety and because it facilitates a coordinated, total systems approach to the storage, transportation, and disposal of spent fuel.

Finally in 1994, the DOE adopted a new baseline, which consists of a much larger and thicker waste package.[5] The waste package would be emplaced horizontally in a drift (rather than vertically in a drift floor borehole). The repository would be designed to remain open (to allow easy retrievability) for a period of up to 100 years, after which backfill may or may not be used. A precise rationale for or explanation of the degree of reliance that would be placed on this engineered barrier system relative to the natural barrier is under study. There has been little experiential research to date on the waste-package materials and no full- or partial-scale testing of any potential components of an engineered barrier system.

Although the differences in geologic and hydrological conditions are great between any potential Japanese site and the Yucca Mountain site (and the level of vigor of the engineered barrier research is less in the U.S.), there may be some benefit to the U.S. program in looking at the process and rationale used in Japan to clarify the role that the various barriers will assume in isolating the waste. This could take place as part of the emerging waste isolation strategy in the U.S. program, which should explain in a comprehensible way what roles different barriers are expected to play in isolating radionuclides.

Hydrology and Geochemistry

In Japan, current thinking is that the following conditions favor containment and longevity of the engineered barrier system: (1) low ground-water flux, (2) reducing anaerobic ground-water conditions, and (3) neutral to moderately basic ground-water acidity. Postclosure performance of the engineered barrier system depends on two major aspects of the natural system — the flux of ground water available to the backfill and the chemistry of that water. (Yamato et al., 1992) A generic approach to performance assessment is being used, in which modeling is carried out, taking into consideration the range of geochemical conditions expected in the ground water.[6] Large-scale, lab-based tests are underway at the Geological Isolation Basic Research Facility at Tokai Works as part of the ENTRY project to ascertain ground-water

4 *In previous reports, the Board made repeated recommendations that the DOE look at a more robust waste package.*

5 *It would contain 21 intact assemblies from pressurized water reactors versus 3 intact assemblies from pressurized water reactors in the former baseline and would be double-walled (about 1 cm of Alloy 825 surrounded by 10 cm of steel) versus the single wall of about 1 cm of 304L stainless steel, 316L stainless steel, or Alloy 825 in the former baseline.*

6 *The range includes: fresh-reducing, low pH; fresh-reducing, high pH; saline-reducing, low pH; and saline-reducing, high pH.*

flow and mass transport in engineered barriers and the surrounding rock and the geochemistry of the ground water.

In addition, in-situ studies have been conducted at the Tono and Kamaishi mines, which among other things, measure stable isotopes to investigate origin, movement, and “residence time” of the ground water; collect water samples from boreholes to examine the chemical properties of ground water; and establish a hydrological monitoring system in a shaft blasted at Tono mine in the sedimentary rock.[7]

In the U.S. program, hydrological and geochemical research also is under way. Work is focused on characterizing one specific site, which was selected for a number of reasons, including potentially beneficial geologic, hydrologic and geochemical properties. The advantage is that, under these conditions, a smaller set of conditions need to be evaluated. Because less is known about the unsaturated zone, however, more extensive site-characterization work may have to be performed. For example, important research is under way at the site to examine percolation movement of water in the unsaturated zone, including the amount of water percolating and the pathways by which it percolates. Computer models also are being developed to predict the hydrologic and geochemical response of the mountain.

A Generic Approach to Performance Assessment Has Been Established

The PNC assessment has taken a generic, as opposed to a site-specific, approach. This approach is made possible by assigning a major role to the engineered barrier system and by defining a small number of critical natural characteristics for a candidate site — conditions that can be met in a variety of geologic settings. Consequently, in PNC’s performance assessment work, no particular rock has been selected for the demonstration of technical feasibility of high-level waste disposal. Instead, direct account is taken of a variety of geologic, hydrological, and hydrogeochemical conditions in different types of geologic situations. Several reasons may underlie PNC’s use of the generic approach, including the absence of a specific site to characterize, the emphasis on engineered barriers as a primary barrier, and a desire for a well-documented scientific approach prior to undertaking site selection.

In contrast, the U.S. program’s performance assessment work is very different. In the United States, one site (Yucca Mountain, Nevada) is being characterized for repository development. As a result, performance assessment is focused on the viability of a potential repository at that site. Furthermore, the DOE is evaluating site suitability according to guidelines (10 CFR 960) that set forth specific conditions to qualify or disqualify the site.

Natural Analogues

Some interesting and potentially useful examples of natural analogues are being studied as part of Japan’s efforts to assess the long-term durability of engineered barrier materials. Perhaps the most interesting examples of natural analogues are 1-million-year-old volcanic glass nodules surrounded by mudstone. The volcanic glass is said to be analogous to glass used in the vitrification of high-level waste, and the mudstone has many similarities to the bentonite surrounding the waste package. The unaltered nature of the volcanic glass argues for the long-term stability of vitrified waste under repository conditions. At the Tono mine, other natural analogue studies indicate that some radionuclides (uranium and thorium) have migrated very little in the past million years. Radium has probably migrated the farthest, that is, at least several meters in the past 10,000 years. Natural analogues also are being used to show differences in the long-term mineralogical stability of bentonite under different temperature conditions.

7 *The purpose of this latter study has been to develop methods and instrumentation for hydrogeologic investigation, to develop a numeric model for evaluating ground-water flow, and to collect data for validation in ground-water flow models (Yusa et al., 1992). At Kamaishi, data have been collected to study the chemical properties, origin, and age of the ground water, and ground-water flow experiments were performed to predict the spatial extent and dimension of water-bearing zones by means of radar tomography (PNC 1993).*

In the past (e.g., NWTRB 1990b and NWTRB 1991b), the Board has supported the potential use of natural analogue studies to increase the current understanding of processes for the transport and alteration of materials over long time periods. At that time, the DOE had a number of analogue-related studies either under way or planned; the DOE also has supported international analogue studies in the past. However, recently, as a result of budget and time constraints, analogue studies are not being pursued as they were in the past.

The Japanese program may offer some important insights on the value of studying indigenous natural analogues, both in terms of building scientific evidence and in explaining important concepts to the public. When using natural analogues, problems may exist concerning the extent to which the analogue is really analogous to the conditions with which one is concerned. If such concerns can be addressed, however, these analogues can provide very powerful and confirming evidence to the public and to the scientific community as to the accuracy of long-term scientific projections.

Overall Approach to Nuclear Waste Management

Underlying the differences in the scientific and technical approaches taken in the programs of the United States and Japan is a fundamentally different approach to the management of their respective nuclear waste programs. This is a result of different historical, political, cultural, and institutional factors — a few of which are highlighted in the following section.

Long-Term Commitment to Reprocessing Spent Nuclear Fuel and Building Energy Independence

The Atomic Energy Commission (JAEC) of Japan recently reaffirmed in its 1994 report (JAEC 1994) Japan's long-term commitment to reprocessing spent nuclear fuel in its efforts to maintain and build the country's energy independence.[8] The JAEC indicated that the Rokkasho-mura reprocessing plant, which will have an annual reprocessing capacity of 800 metric tons, is under construction and will be commissioned shortly after the year 2000. Also indicated was that a decision on the capacity and technology of a second reprocessing plant will be needed in around 2010 to ensure handling of all of the spent fuel that eventually will be generated by Japan's reactors (currently 46 reactors at 7 sites with the potential for 7 new sites in the foreseeable future).[9]

Members of the JAEC state their belief that uranium resources will become much more valuable by the middle of the next century. They believe nuclear energy, combined with conservation and development of alternative energy sources, will be required in the energy mix. The JAEC also states that the world's increasing demand for energy (90% of which comes from fossil fuels) will exhaust supplies if the demand continues to grow at its current rate. The JAEC calls for nuclear fuel recycling to increase the effective use of uranium resources. The JAEC makes a case for energy independence, the use of nuclear energy for only peaceful purposes, and the promotion of nuclear power combined with other energy sources worldwide.

In contrast, the prospects for reprocessing civilian spent nuclear fuel in the United States were effectively dead by the early 1980s. Some of the reasons for the development of U.S. policy in this direction are outlined in the Board's 1993 summary report (NWTRB 1994b).

8 *This commitment was also noted by the Board in its visit to the integrated fuel cycle center at the Rokkasho-mura site, where a full-scale commercial reprocessing facility is being built, and in its tour of a demonstration reprocessing plant at Tokai Works.*

9 *The Japanese have designed a unitized approach to building a reprocessing plant; it permits expansion through the addition of units as needed.*

No Disposal Agency, No Potential Sites, and No Regulations

In Japan, no implementing waste disposal agency or potential sites for a permanent repository currently exist, and there appears to be no rush to establish either. Safety regulations address radiation standards for people, but none exist specific to disposal. The Japanese approach, which is quite the opposite of that emerging in the United States, is to defer all decisions about siting until such time as the following are completed: extensive generic nuclear waste R&D, site-specific research in two underground research laboratories, technically sound disposal of low-level waste, operating reprocessing facilities, and long-term storage for high-level reprocessing waste. In its most recent report, the JAEC states it this way:

> *The most important remaining task for the sake of ensuring a consistent system of nuclear power generation is the establishment of ways of appropriately accomplishing treatment and disposal of radioactive waste and decommissioning. The tentative target for the disposal site is the 2030's or by around 2045 at the latest, but the actual decision on construction and commissioning will be made on the basis of comprehensive judgment that takes into account the time needed before construction of the disposal facility, the rate of progress in the reprocessing program, and other future circumstances in Japan's development and utilization of nuclear energy (JAEC 1994).*

Based on the many ongoing developments in Japan's nuclear program, it is clear that a strong emphasis remains on pursuing a full-scale expanded nuclear power program, while the decision has been made to move very deliberately and without regard to time schedules toward safely disposing of high-level waste. This more deliberate pace may reflect both the existence of adequate interim storage capability for high-level waste and a slowdown of the program following the protests that took place in the late 1980s against efforts to site nuclear facilities. In Aomori prefecture, for example, more than 10,000 people demonstrated in 1989 against the establishment of an integrated fuel cycle center at the Rokkasho-mura site.[10]

A step-wise approach to developing a permanent high-level waste repository has evolved, as reflected in changes in national law and organizational responsibilities. The emphasis is now placed on developing and testing a waste management system concept in ways that are understandable and explainable to the public, combined with extensive in-situ work that will help explain the performance of several geologies under the volcanic, seismic, and ground-water conditions common to Japan.

In the United States the situation is different. In 1982 a federal statute (the Nuclear Waste Policy Act) required the DOE to enter into contracts with the utilities to dispose of civilian spent nuclear fuel. According to some nuclear utilities and state commissions that regulate consumer rates, the DOE is contractually obligated to take title to the spent fuel for disposal no later than January 31, 1998. Although the Nuclear Waste Policy Act holds the DOE responsible for disposal, the act holds the utilities responsible for storing the fuel on an interim basis. In the Nuclear Waste Policy Amendments Act of 1987, the U.S. Congress narrowed potential repository sites from three to one; a site at Yucca Mountain, Nevada, was identified as the single site for characterization. Current U.S. policy directs the DOE to characterize the site. If it is determined suitable by the DOE, then the Secretary will recommend the site to the U.S. President, who, in turn, would make a recommendation for development to the U.S. Congress. The potential host state, Nevada, can veto the President's designation, but the final decision rests with Congress. If Congress approves the site, an application for a license to construct a repository will be submitted to the NRC.

Consequently, in the United States, under ongoing pressure from the utilities — which want timely waste removal from their premises — the DOE[11] is attempting to characterize the Yucca Mountain site

10 *Despite the public protests of 1989, all the facilities — a low-level waste disposal site, reprocessing plant, spent fuel storage pool, and high-level vitrified waste storage facility — were either in operation or under construction during the Board's visit.*

with all due speed. This process has been subject to revised schedules as deadlines have been missed. The DOE's *current* goal, should the Yucca Mountain site be found suitable as a potential repository, is to submit a license to the NRC by 2001 and to begin emplacing the spent fuel by 2010.

R&D Work Versus the Eventual Characterization, Siting, and Construction of a Repository

In Japan, the policies that have been enacted over the past few years are centered on a desire to separate completely the generic research R&D work leading up to the siting of a potential repository and the process of selecting and characterizing a potential site and building a repository. The effort to separate the two officially began in 1992 in a report issued by the JAEC's Advisory Committee on Radioactive Waste. This report established a new "vision" to help implement Japan's high-level radioactive waste disposal program. The JAEC reiterated this policy in its 1994 policy report.

As the policy has evolved, the national government assumed responsibility for ensuring final disposal. Then, in 1993, the Steering Committee on High-Level Radioactive Waste Project was created to help facilitate smooth implementation of the high-level waste disposal program. PNC has been given responsibility for building a comprehensive and easily understood generic disposal research and development program, followed by the siting of more than one underground research laboratory to study the characteristics of Japanese geology and other conditions.[12] During the Board's visit, the Japanese stressed that their R&D work was generic in nature and not related to siting a repository. In the case of R&D work at the Kamaishi mine, the PNC has even agreed to cease all in-situ work in 1998 to assure the surrounding localities that the mine will not be developed into a permanent repository.

In contrast, the U.S. program has evolved into one where both generic, above- and below-ground research, and, repository-specific research are being focused at the same location — Yucca Mountain, Nevada. The DOE has the task of performing generic and site-specific research, determining site suitability, and if suitable, submitting various license applications for an operating repository in approximately 15 years.

Provisions For Long-Term Interim Storage

Japan's basic policy calls for reprocessing spent fuel, and conditioning and stabilizing the high-level radioactive waste in solid form in stainless steel canisters, followed by storage for 30-50 years. The purpose of long-term interim storage is to cool the waste to well below boiling prior to disposal. The utilities in Japan have been given and have accepted responsibility for the long-term interim storage of all their wastes as well as the disposal of low-level waste. Japan Nuclear Fuel Limited, in addition to constructing a shallow land burial facility for the disposal of low-level waste and a full-scale spent fuel reprocessing facility, is building a facility for the long-term storage of high-level reprocessed waste to be returned from overseas, and a storage pool for spent fuel at the Rokkasho-mura site. These facilities, combined with at-reactor pool storage, will provide sufficient interim storage for high-level waste and disposal capacity for low-level waste for the foreseeable future.

As already mentioned, in the United States the utilities are responsible for spent fuel storage until acceptance for disposal by the DOE. As a result, the United States does not have a specific plan for *long-term* interim storage for its civilian spent nuclear fuel; where needed, interim storage will be taking place at reactor sites until the DOE begins receipt of the spent fuel. Because repository operations — originally planned for 1998 — have been delayed,[13] questions about long-term storage have arisen, particularly

11 The U.S. Congress has designated the DOE the implementing agency for managing civilian spent fuel disposal.

12 The nuclear utilities were assigned the role of paying for disposal and playing a role even in the research and development stage.

13 Current DOE projections put the date for repository operations to begin in 2010.

among utilities who are running out of pool storage space. The DOE sees a partial solution to the interim storage question in the creation, licensing, and deployment of multipurpose canisters. If the DOE can design these canisters and have them licensed by 1997, then the DOE believes it would be able to begin delivering the canisters to the utilities in 1998. These canisters would be filled with spent fuel, sealed, and dry-stored at reactor sites until a site for a centralized interim storage facility is found or the repository begins operations.[14]

Public Information and Outreach

Despite many differences, both the Japanese and the U.S. nuclear waste programs must gain broad public understanding and acceptance of the risks involved before any spent nuclear fuel or high-level waste will be disposed of.[15] Different approaches aimed at gaining public understanding are emerging. These range from the U.S. challenge of increasing public understanding of risks involved in spent fuel disposal early in the process, even as the site-characterization work is going on, to the Japanese approach,[16] which appears to be to increase public understanding of the generic issues involved while delaying the decision to select a site. Instead, the government of Japan has indicated it will revisit efforts to site a repository in the distant future. For the time being, the Japanese are developing a strong generic R&D program aimed at building a solid professional consensus and informing the public on the scientific and technical dimensions of the risks involved in disposing waste over a long period of time.[17]

International Outreach

Those involved in the scientific and technical work in Japan's nuclear waste program have extensive and continued contact with their counterparts in many countries. Young scientists from PNC are sent abroad for extensive periods of time to work on specific experiments, pick up emerging research tools and techniques, and become more involved with the international technical community. This seems to be done in a fairly systematic fashion so that the knowledge these individuals have gained can be put to long-term use when they return to Japan. This approach seems to contribute to Japan's ability to adapt the best approaches, thoughts, and work from other countries' programs in developing its own. Perhaps this approach and the ensuing benefits are possible in Japan because employees tend to spend their careers in the same field with the same organization or company. It may be worth exploring to see if some variation on the Japanese approach could be initiated in the United States — perhaps a variation more conducive to the nature, style, and organization of the U.S. program.

Conclusions

The U.S. program for nuclear waste management and disposal differs from its Japanese counterpart. In Japan, spent fuel is reprocessed domestically and abroad. A strong national policy exists to expand nuclear production and to improve Japan's capability to do so. Long-term interim storage is an integral part of the program and is generally accepted. No organization will be assigned responsibility for high-level waste disposal until after the year 2000, and there are no regulations explicitly governing the disposal of high-level waste. There will be no efforts to designate a specific repository site for many years to come, and every effort has been made to separate current generic R&D work from an eventual decision to select a site.

The Japanese have adopted a cautious, step-wise approach to developing a permanent repository program. This approach reflects a concerted effort to

14 The DOE also had been supporting the work of the U.S. Nuclear Waste Negotiator to secure a volunteer host for such an interim storage facility, but a volunteer site was not designated, and the negotiator's office has recently been closed.

15 In fact, all of the programs in the countries visited by the Board to date share this challenge.

16 Also the Canadian approach, and to some extent, the approaches being used in France and Sweden.

17 Canada has also taken this approach.

distinguish between nuclear waste R&D work and eventual site-selection and characterization work. So, although facing the prospect of siting, designing, and constructing a repository in difficult geologic and hydrologic conditions, those involved in Japan will have the benefit of decades of R&D work worldwide in the geology eventually selected. A fairly detailed approach has been articulated. This includes the use of multiple, engineered barriers to contain the waste and to build reliability and safety into the system. The approach will be tested through extensive generic, laboratory-based, and underground research well *before* a permanent site is selected or disposal safety standards are promulgated. The tentative target date is to commission a repository in the 2030s or by approximately 2045 at the latest.

In contrast, the United States has chosen to dispose of its spent fuel directly and as soon as possible. In response to public and political outcry in the 1980s over efforts to select two sites nationwide, the U.S. Congress chose to react in a very different manner from the Japanese, who slowed down their program in the face of similar public outcry. Instead of abandoning the site-selection process, the Congress selected Yucca Mountain as the sole site to be characterized. The Congress assigned the DOE the responsibility of performing generic and site-specific research, determining site suitability, and submitting a license for a repository in approximately 15 years time. The DOE's original plan had been to rely heavily on the natural geology to isolate the radionuclides, using a thin-walled waste package emplaced in vertical boreholes located in drifts well above the water table. This approach is changing, however, and a precise rationale for or explanation of a strategy for relying on specific engineered and natural barriers for performance is just emerging.

In addition, while the DOE is continuing work to satisfy the present safety standards and regulations set forth by the EPA and the NRC, these regulations are subject to change pending the outcome of a congressionally mandated review being conducted by the National Academy of Sciences. In the meantime, spent fuel remains stored at nuclear reactor sites.

Recommendation

After a review of the radioactive waste management program in Japan, the Board recommends that the U.S. program examine and keep abreast of activities under way in the Japanese program in the six specific areas listed below.

Whether Japan or the United States will be able to site and build a repository that the public deems safe remains to be seen. Each country has taken a very different approach to implementing its respective disposal program for high-level waste and spent nuclear fuel. In making its trip to Japan, the Board asked itself if, "given these differences, are there any insights to be gained from the Japanese program that are of potential benefit to the U.S. program?"[18] The Board identified six areas.

Seismic and volcanic hazard assessment. Because Japan is prone to active faulting, earthquakes, and volcanism, PNC is conducting extensive research into the potential effects of earthquakes and volcanoes on the geology and hydrology. It might be helpful for the U.S. program to keep abreast of this work, to determine if it provides any insights into whether earthquake-induced changes in the hydrologic regime of the potential site at Yucca Mountain, Nevada, are a significant concern.

Engineered barriers. Because the nature of geologic conditions in Japan prevents an exclusive reliance on the natural barriers for repository performance, emphasis has been placed on designing a multi-barrier approach that includes a very robust EBS. There may be some benefit in looking at the rationale and approach the Japanese have developed as the U.S. program works to define more precisely potential EBS and the natural barrier roles in containing and isolating waste in the unsaturated and saturated zones, as at the potential repository site at Yucca Mountain, Nevada.

18 There most likely are certain aspects of the U.S. nuclear waste disposal program from which the Japanese program could benefit, too, but that was not the focus of the Board's trip.

Natural analogues. In Japan, analogue studies are being conducted to assess the long-term durability of potential materials that could be used in an engineered barrier system and in the mobility of natural radionuclides. There may be some important insights in this work for the U.S. program, both in terms of building scientific evidence on the very long-term geologic processes and in explaining important and difficult-to-understand concepts to the public.

Accepted long-term plans for interim storage. The Japanese have developed long-term interim storage for high-level waste that seems acceptable to the government, utilities, and general public. In contrast, the DOE has been seeking for years a solution to long-term interim storage of spent nuclear fuel that is acceptable to the industry and general public. Some U.S. nuclear utilities do not want to store their spent fuel at their reactor sites, and the vast majority of the public does not want spent fuel stored near them, especially if that fuel is from other states. The U.S. program might gain some insights by looking at how Japan assigns responsibility for interim storage of spent fuel and high-level waste, as well as the political and institutional developments that resulted in the creation of the Rokkasho-mura integrated fuel cycle center, where spent fuel and high-level waste storage facilities currently are under construction.

The importance of generic R&D work versus site selection and characterization work. The Japanese policies enacted over the past few years have centered on completely separating the generic research and development work leading up to the siting of a repository from the process of selecting and characterizing a potential site. Although there may be disadvantages to this approach from a scientific and technical perspective, one advantage may be that the overall high-level waste disposal program will be implemented more gradually and smoothly and better understood. As a consequence, the approach may be more acceptable to the general public. Although Congress requires the U.S. program at present to conduct site-specific research and development, there may be some benefit in looking at the effects in the Japanese program of separating generic R&D from site-selection activities. This review could be done with an eye toward building a comprehensive and sound scientific and technical program.

International outreach. Those involved in the scientific and technical work in Japan's nuclear waste program have extensive and continued contact with their counterparts in many other countries. This is done in a systematic manner, which includes sending young scientists abroad for a number of years to conduct research and learn from the programs of other countries. Although the U.S. program has sent many scientists overseas in collaborative projects, it seems to have been organized very differently. There is not the same continuity in employment within U.S. organizations, and it may be worth exploring to see if some variation of Japan's approach could be initiated in the United States.